Advanced Modeling of the Navy Operational Environments

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UGC 2001

Biloxi, MS, June 18-21, 2001

Collaborators and Acknowledgements

- Collaborators: D. Marble, J. Pelton, P.-M. Poulain, D. Stark, A. Semtner, L. Shu, R. Tokmakian, and W. Walczowski.
- Visualization: NAVO MSRC (Gruzinskas, Haas, Goon), D. Ivanova, W. Walczowski (NPS)
- Computer Resources: DOD HPCMO: NAVO, ARSC, ARL. ACL @LANL.
- Data: AOML, JEDA,WOCE DACs, U of H, BODC
- Funding: ONR, NSF, DOE/CCPP

Navy Prediction Vision

- A coupled Pan-Arctic ice-ocean model that provides operational forecasts of sea ice and ocean conditions.

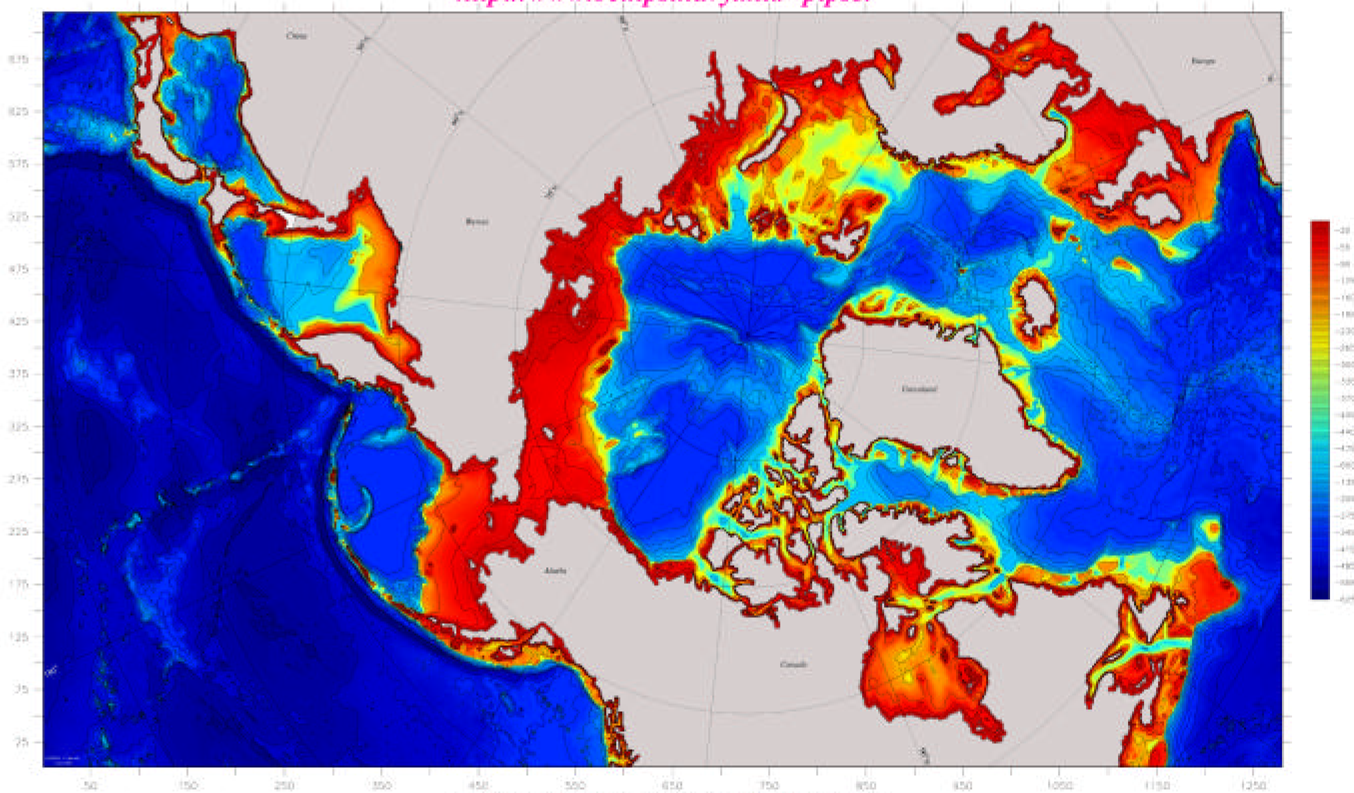
- A high-resolution global coupled air/ocean/ice prediction system.

- Very-high resolution regional coupled models nested into the global system at strategic locations.

PIPS 3.0 Model Development

Naval Postgraduate School - Arctic Modeling Effort

http://www.oc.nps.navy.mil/~pips3/



1/12 Degree PIPS 3.0 Model Bathymetry (m)

(Data derived from ETOPO5 database; Navy Research Lab, Canadian Hydrographic Service and Russian charts; and declassified U. S. Navy and British Royal Navy submarine bathymetry data. Contour intervals: 10, 25, 50, 100, 200 and 500-6000m, by 500m)

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Naval Postgraduate School, Monterey, CA

Polar Ice Prediction System (PIP3.0)

- Ocean model: POP (1280x720x45)
- Sea ice model equations solved as a set of coupled initial/boundary value problems using a staggered Arakawa-B grid.
- Details of numerical approach: Bitz (2000).
- Viscous-plastic rheology and the zero-layer approximation of heat conduction through ice.

Parallel Ocean Program (POP)

- Primitive equation z-level ocean model with a free-surface boundary condition.
- Approximations to governing fluid dynamics equations permit decoupling of model solution into barotropic (vertically-averaged) and baroclinic (deviations from vertically-averaged) components; solved using implicit elliptic and explicit parabolic equation systems, respectively.
- Fortran90
- Designed to run on multi-processor machines using domain decomposition in latitude and longitude.
- MPI for inter-processor communications on distributed memory machines and SHMEM on shared memory machines.
- http://climate.acl.lanl.gov

PIP3.0 Approach

<www.oc.nps.navy.mil/~pips3>

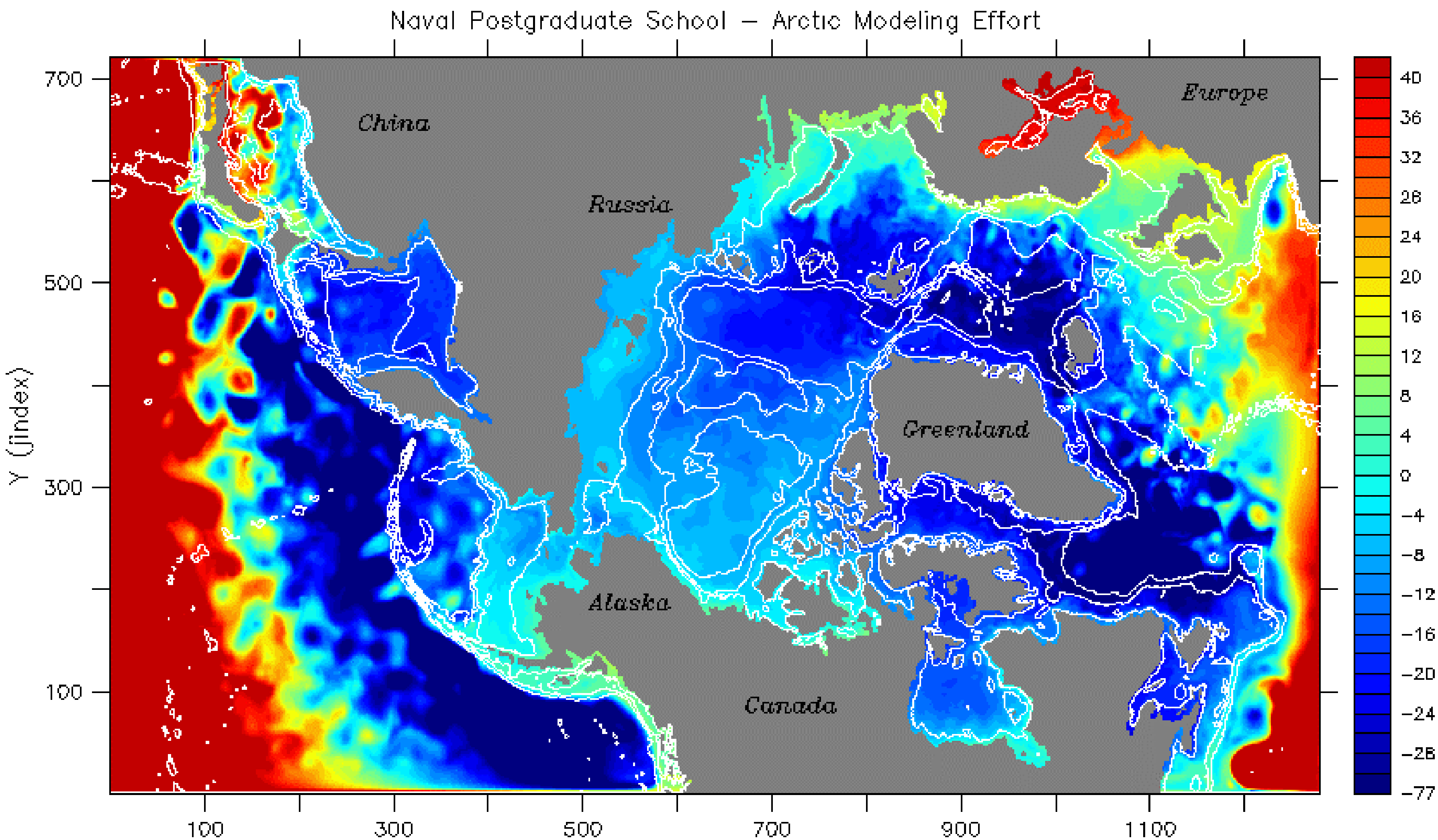
Complete a **40-year** spinup of the 9-km coupled ice/ocean model forced with ECMWF climatology using the T3E900 at ARSC (35 min/24 hours on 128 PEs) using:

- the 2.5 km International Bathymetric Chart of the Arctic Ocean (IBCAO) digital bathymetric product.

<http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html>

- the University of Washington/Polar Science Center Hydrographic Climatology (PHC):

<http://psc.apl.washington.edu/Climatology.html>



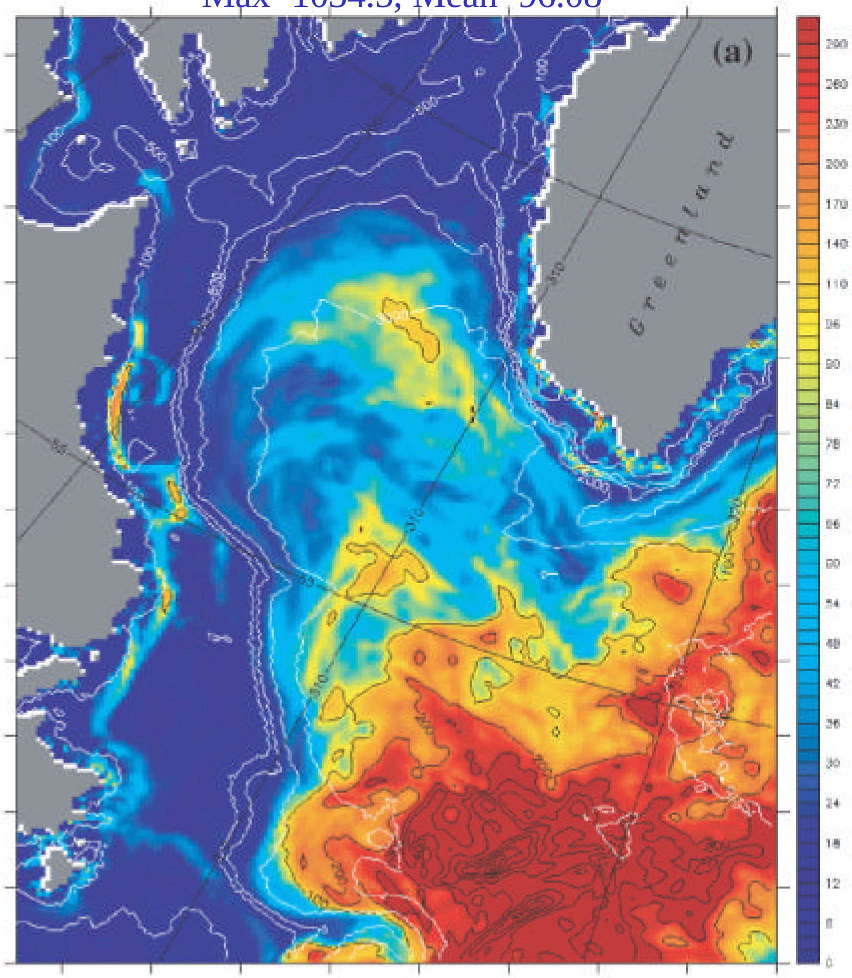
Sea Surface Height (cm) - August/Year13 PIPS3.0 Spinup

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Movie of daily snapshots of the surface (0-5m) eddy-kinetic energy (cm^2/s^2) in the Labrador Sea from PIPS 3.0 Spinup Year 18

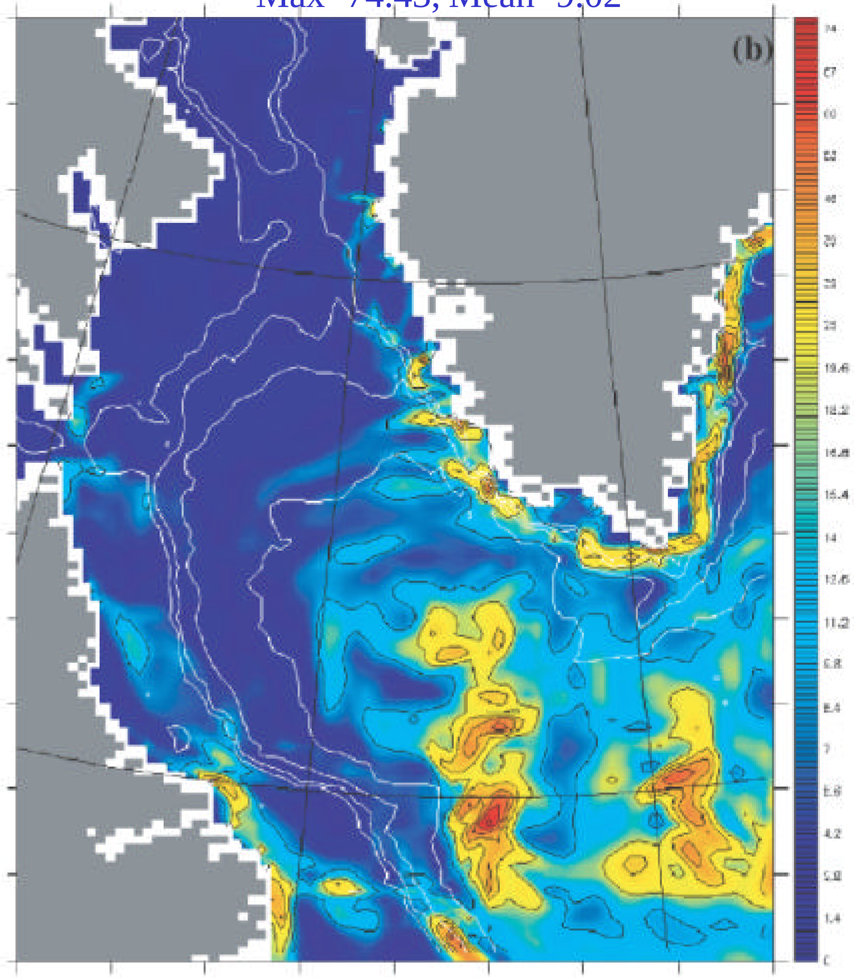
- Comparison of surface eddy kinetic energy (cm^2/s^2) in the Labrador Sea from the (a) 9-km and (b) 18-km model - ~10% of (a)

Max=1034.5, Mean=96.08

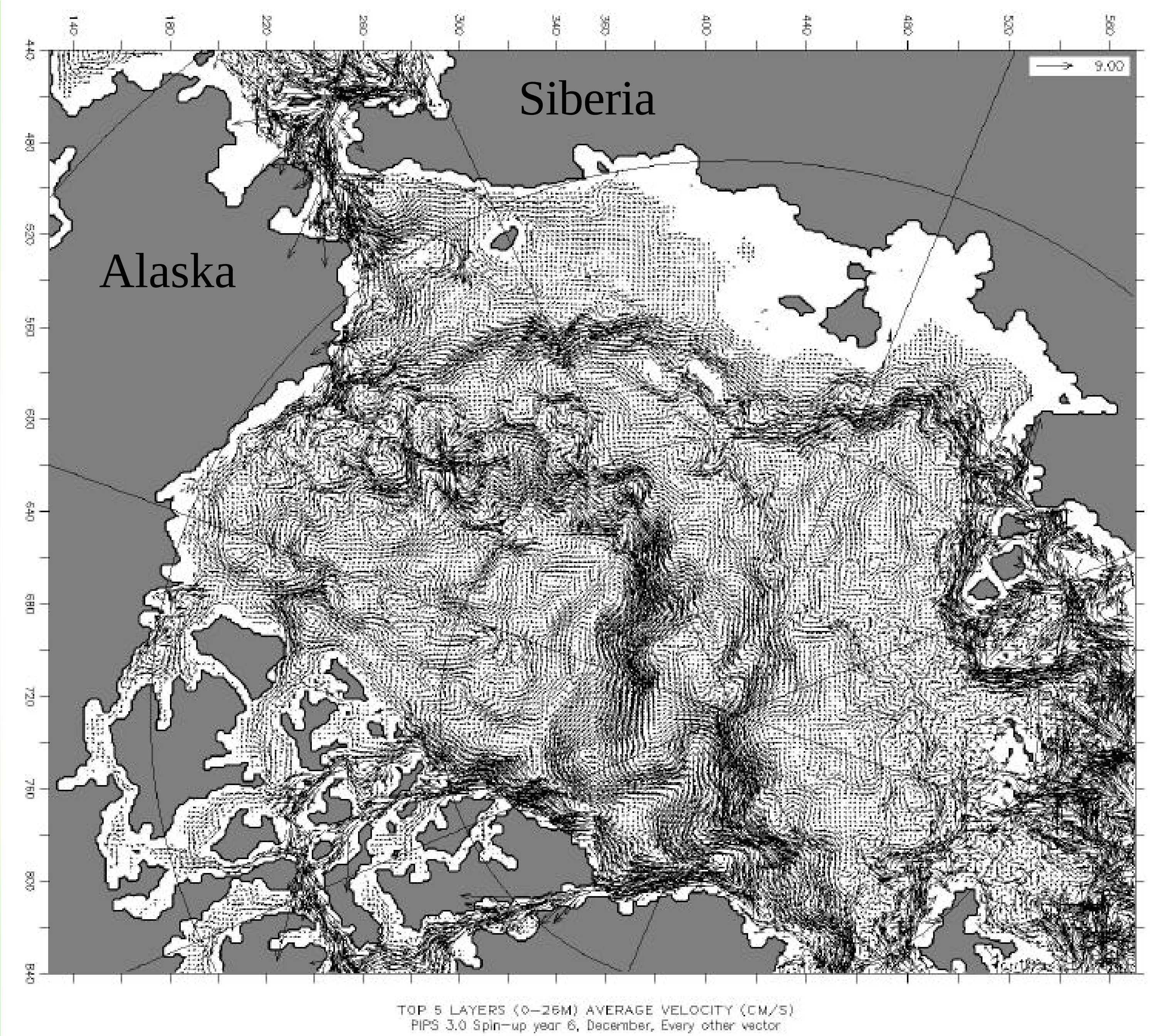


PIPS 3.0 Spinup Year 13, depth = 0-5 m

Max=74.43, Mean=9.02

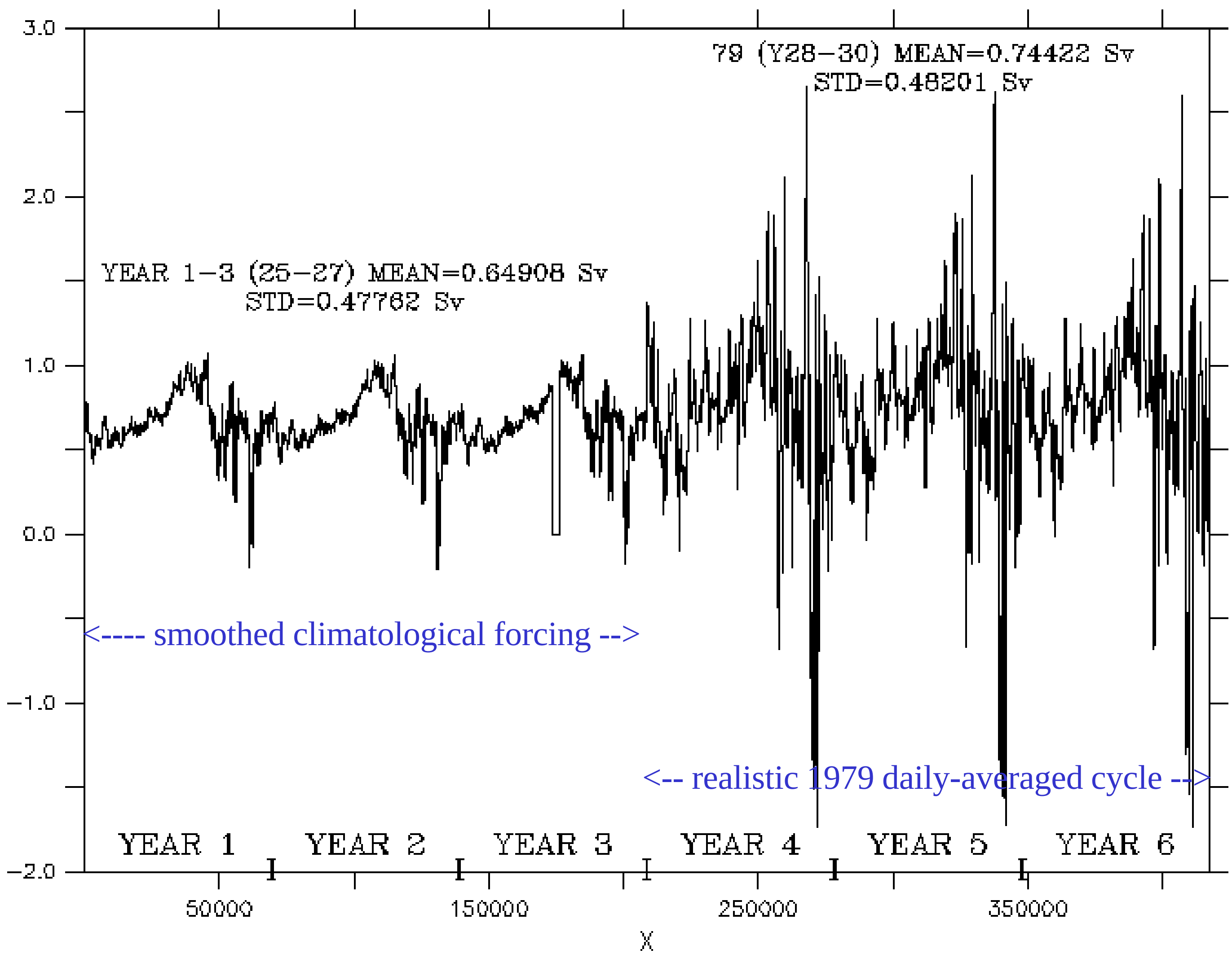


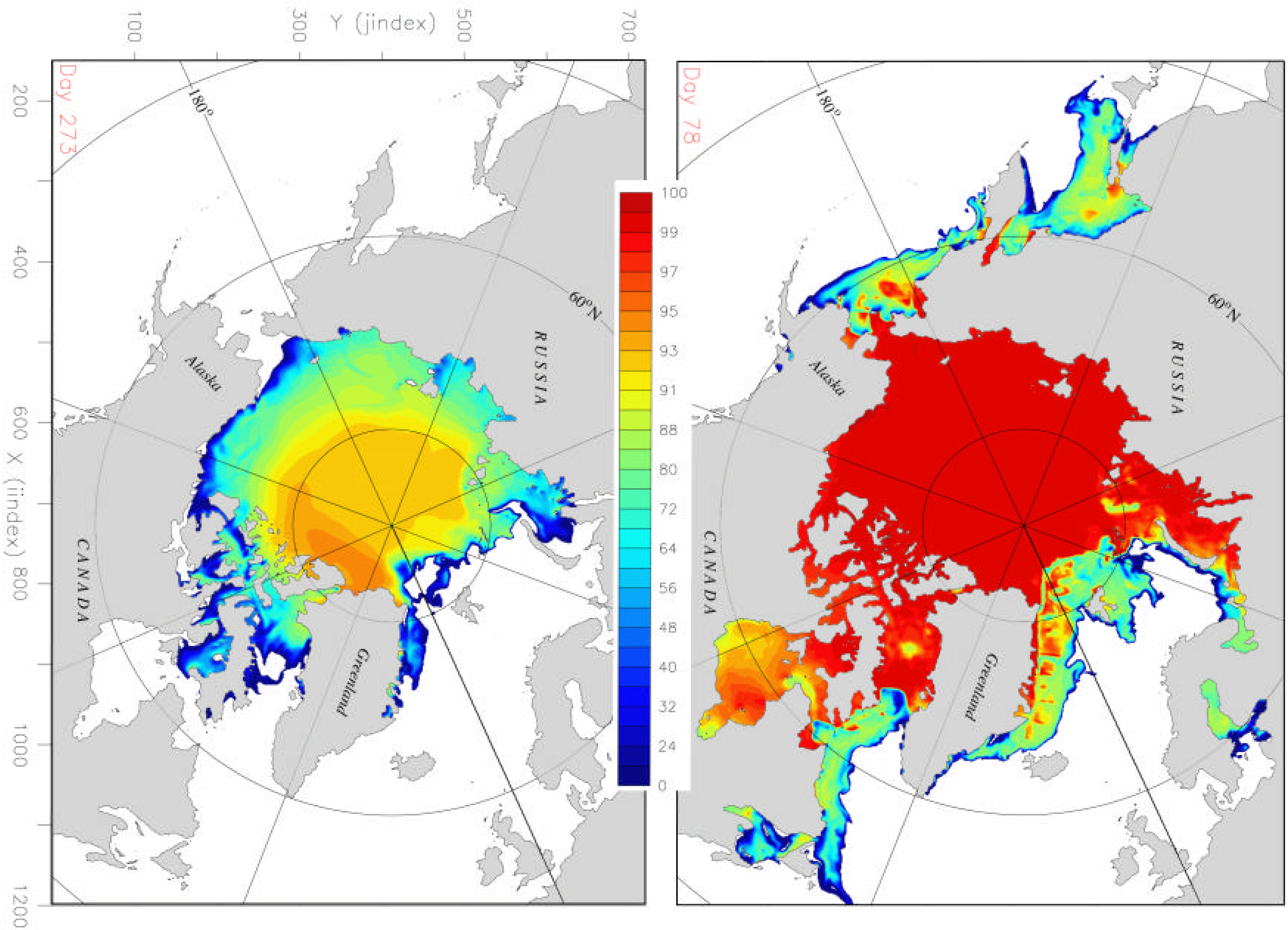
PCAP18 Year 1997, depth = 0-20m



A snapshot of the Arctic Ocean circulation at depth 0-26 m.

Predicted Volume Transport through Bering Strait



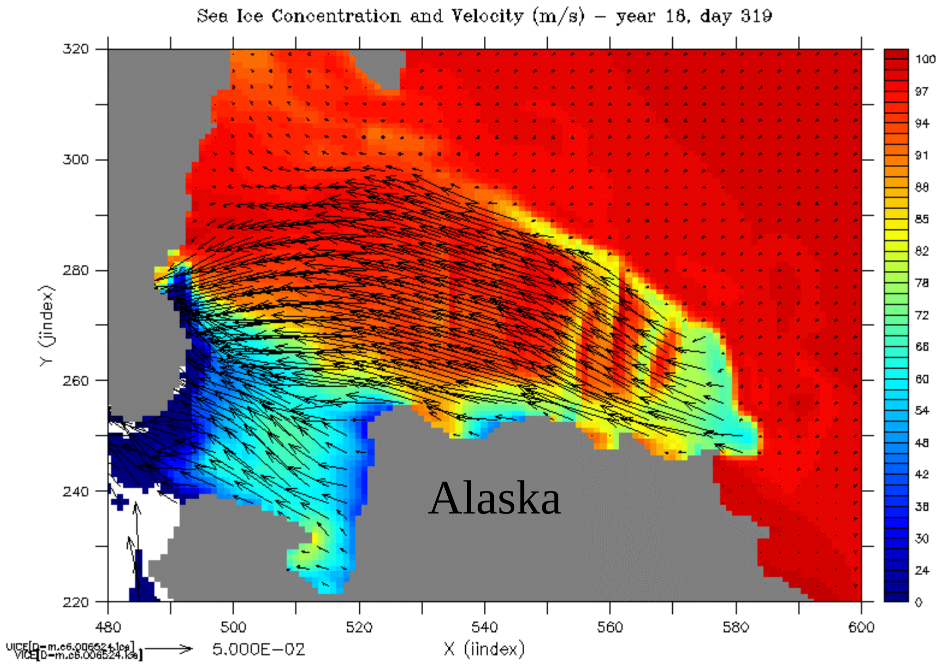


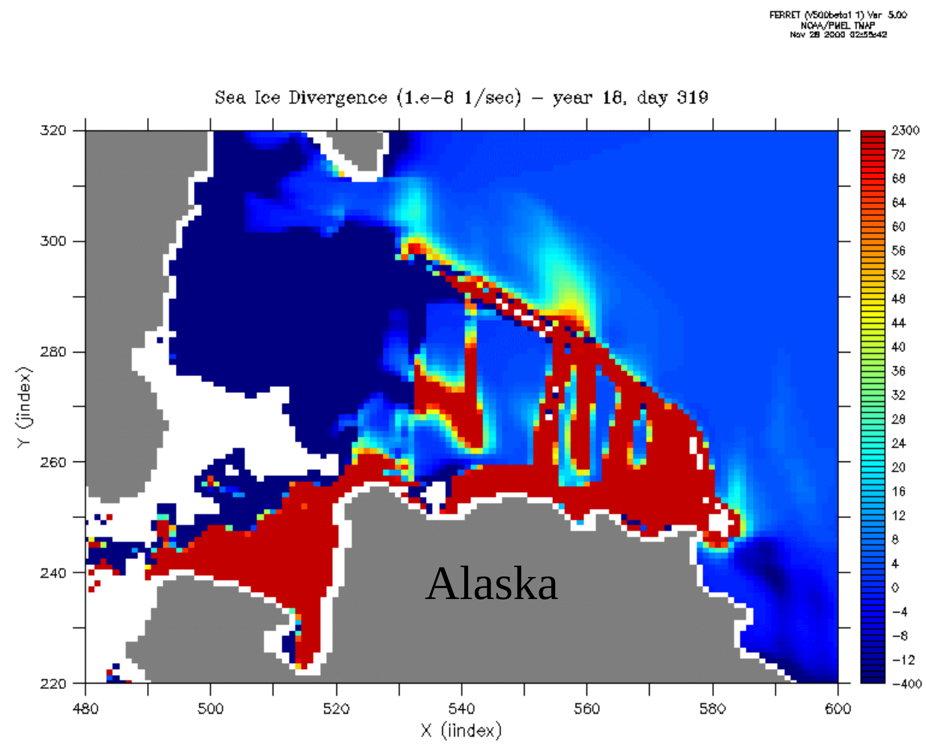
- Sea ice concentration (%) in (a) winter and (b) summer

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Daily sea ice concentration (%) **movie** from PIPS 3.0 Spinup Year 18

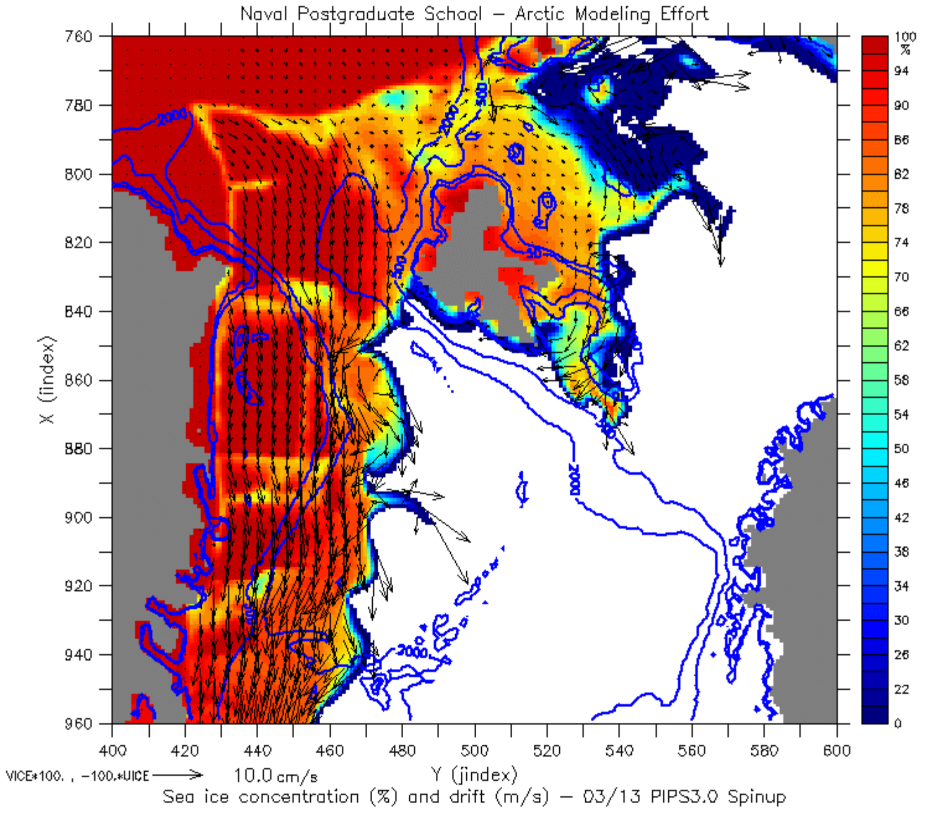
Sea Ice Concentration (%) and Drift (m/s) (left) and Divergence (right) - PIPS 3.0 Spinup Year 18, Day 319

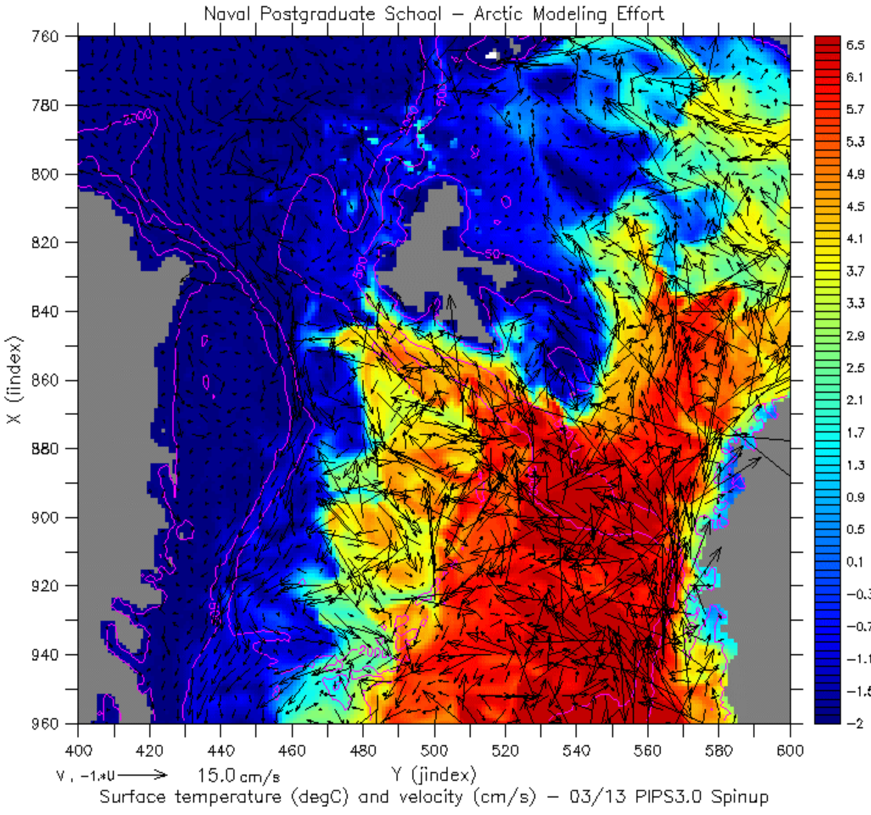




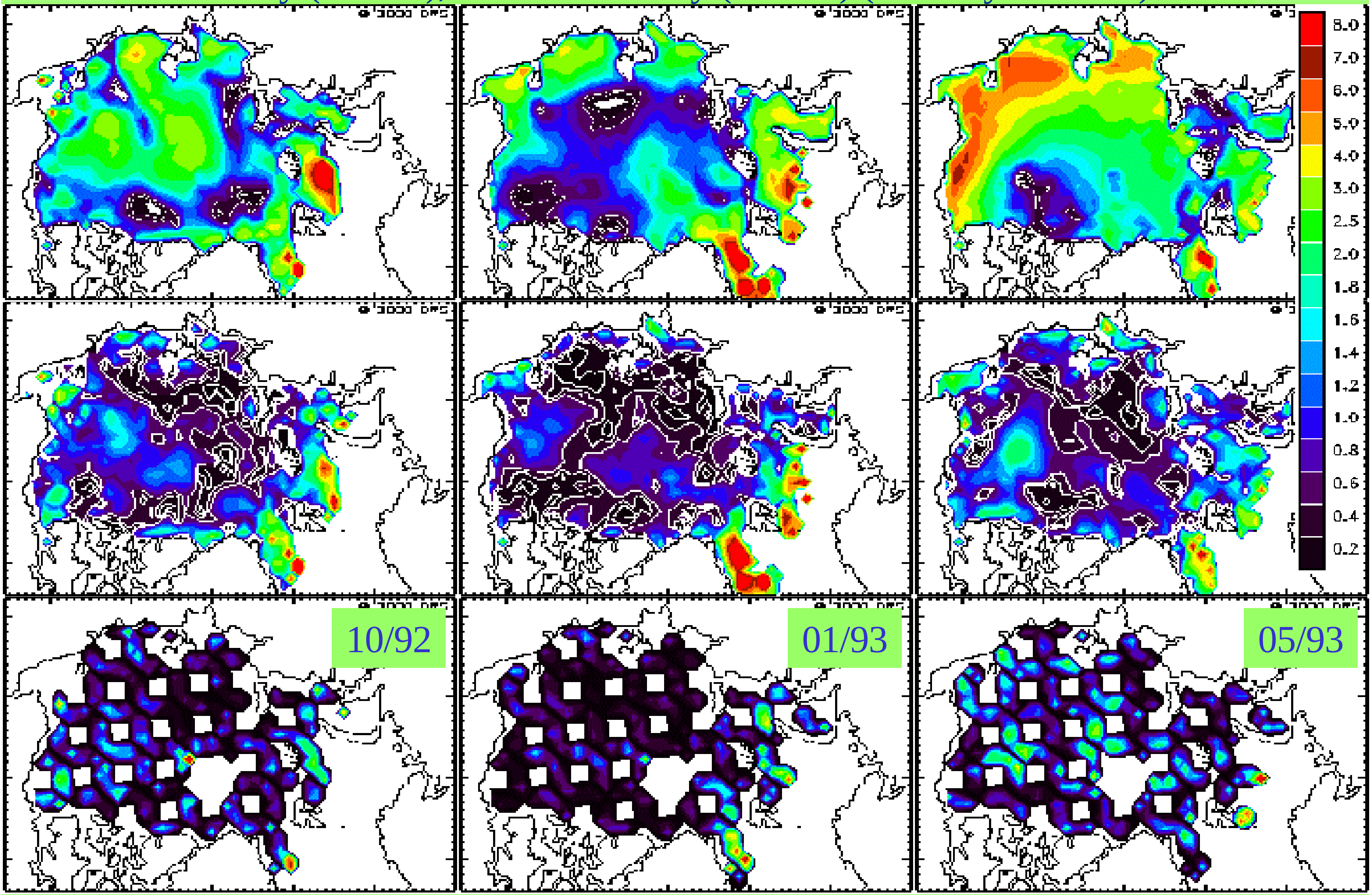
$$div = \delta u / \delta x + \delta v / \delta y$$

Sea Ice Concentration (%) and Drift (cm/s) (left) and Sea Surface Temperature (°C) and Velocity (cm/s) (right) in the **Nordic Seas - 03/13** PIPS 3.0 Spinup





Monthly-averaged absolute error (cm/s): model-buoy (top), assimilation-buoy (middle), and SSM/I-buoy (bottom) (courtesy D. Stark)



Results and Continued Approach:

1. Realistic representation of seasonal ice variability in the Northern Hemisphere, including ice concentration, thickness, leads and polynyas, ice edge and marginal ice zone (MIZ).

<www.oc.nps.navy.mil/~pips3>

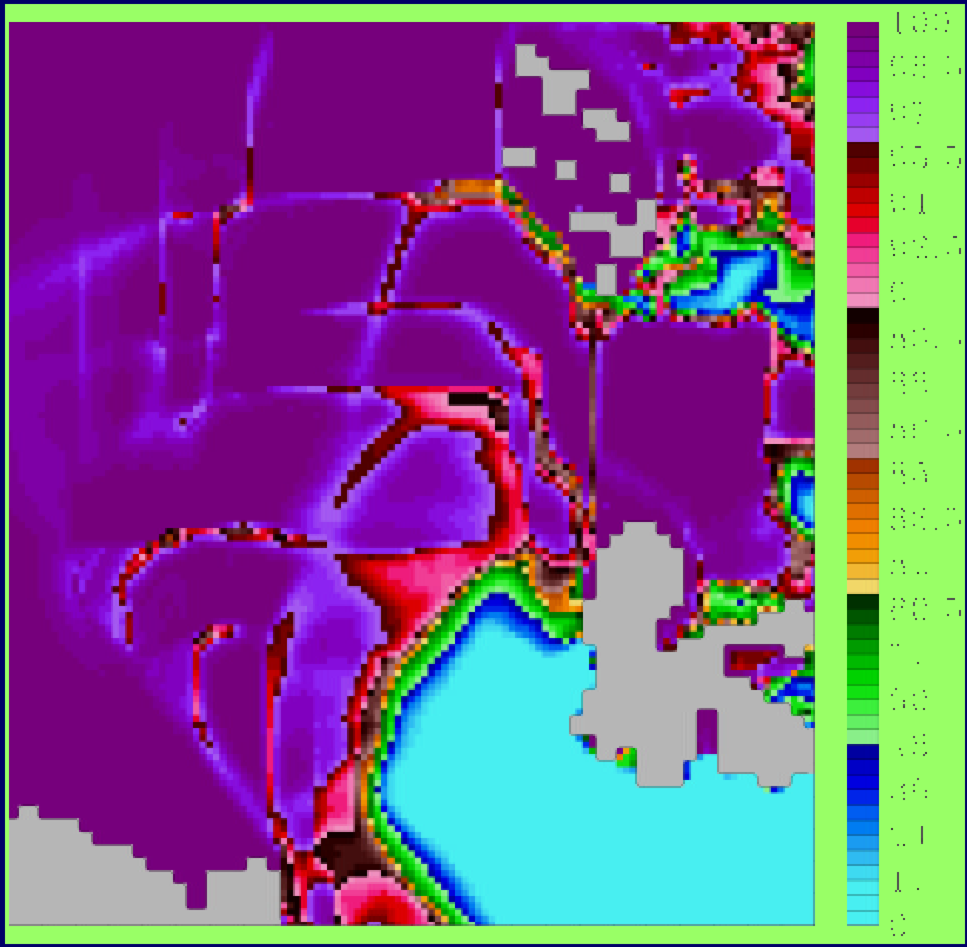
2. Mean 1979 Bering Strait transport : 0.75 Sv (observed mean ~0.8 Sv <www.psc.apl.washington.edu/HLD/Bstrait/bstrait.html).

3. Improved representation of the time mean and eddy energy fields, boundary currents, shelf-basin and inter-basin exchanges of volume, heat and salt.

5. Evaluation and implementation (in progress) of the new sea ice thickness distribution model with energy-conserving thermodynamics (Bitz, 2000).

6. Continued tests of the assimilation method (Meier et al., 1999) using the sea ice motion fields derived from SSM/I in the model <www.oc.nps.navy.mil/~stark/assimilation.html> .

New Sea Ice Model Development



Sea Ice Concentration (%) to the north of Fram Strait from the 9-km stand-alone ice model with the same domain as the 18-km model

Improvements:

- 9-km Extended Horizontal Grid
- Multi-Category Thickness Distribution (5)
- Multi-Layers to allow non-linear T&S profiles
- One Snow Layer on top of each category

Conclusion

Models of the Arctic Ocean and sea ice:

- are converging on proper scales, intensities, and time variability of real ocean

- provide useful guidance to collection and interpretation/synthesis of field observations

- have potential to assess predictability and make predictions on short to long time scales when used with suitable atmospheric models

Future Tasks:

1a. Complete development of the 9-km coupled model and 40-50-year production run with realistic interannual forcing (resource&storage)

1b. Assess improvements due to new ice-ocean parameterizations and assimilation methods in sea ice prediction using the PIPS 3.0.

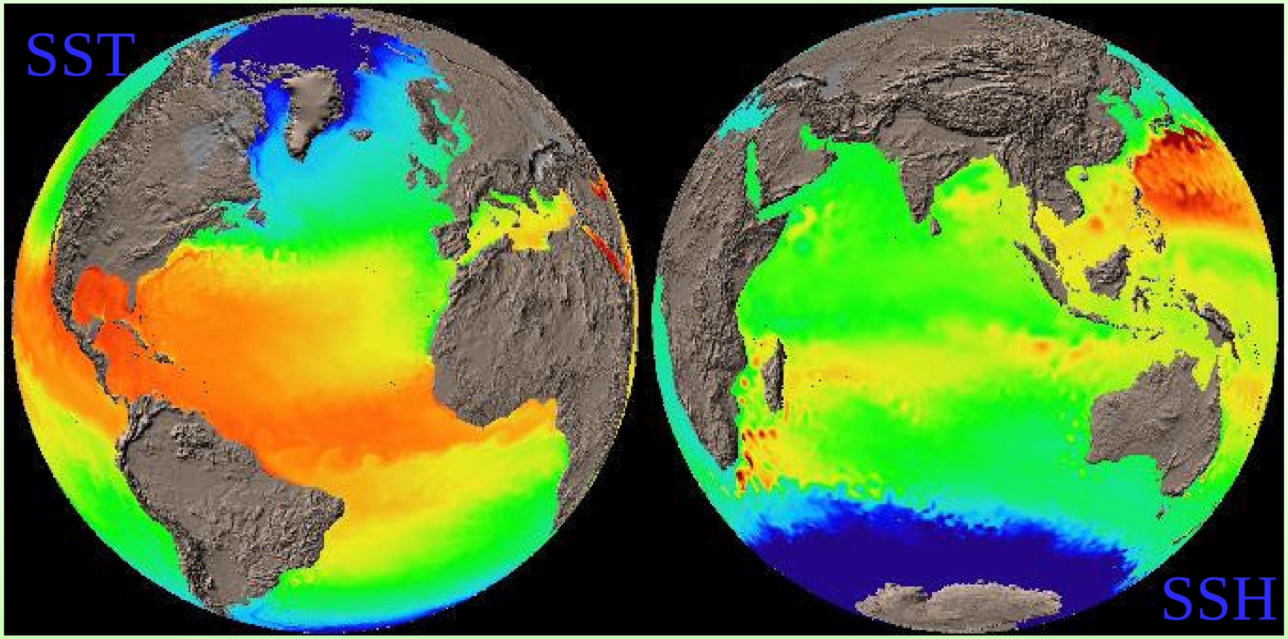
1c. Provide support for the model transition into the operational mode

2. Develop an eddy resolving coupled ice-ocean model of the Arctic Ocean at 1/48^o (~2.3 km)and 38-level nested in the large 9-km model (~8xPIPS 3.0 - large system requirement: 256-512 PEs, local and archiving storage)

3. A regional Arctic climate model (at sufficiently high resolution) should provide predictive capability for the region at daily to interannual scales

4. Regional (nested) approach might be required for proper representation of the Arctic region in global climate models

0.1° 40-level global POP



McClean (NPS) and Maltrud (LANL)

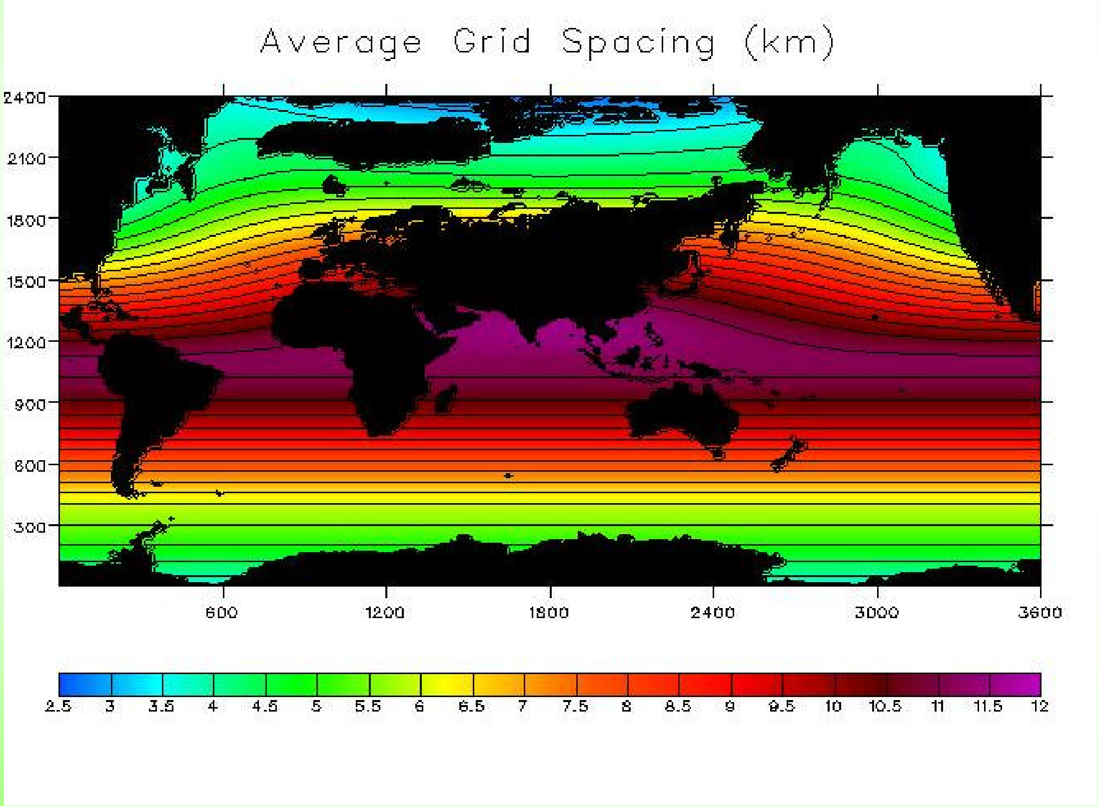
Global Ocean Objectives

- Perform a two-decade spin-up of a high-resolution global configuration of POP.
- Analyze boundary currents, transports, overflows, water mass characteristics and energy levels during spin-up.
- After the spin-up, integrate using nearly a decade of Navy forcing: very-high frequency momentum, heat, and freshwater fluxes.
- Provide a realistic, high resolution ocean state for:
    - Data assimilation and forecasting
    - Coupling with the Navy's global atmospheric model,
    - lateral boundary conditions to regional models.

Approach: 0.1º, 40-level Global POP Spin-Up Description

- Multi-level PE model; Implicit free-surface
- Fully global displaced North Pole grid
- 3600x2400x40 grid points
- POP release 1.3
- ``Natural'' spin-up from rest: Initialized from blended 1/8º MODAS (January) and POLES (winter) PT and S (Piacsek)
- Topography: Sandwell and Smith (71S-67N), IBCAO (66N-90N), & BEDMAP (66S-79S). Modifications to encourage more realistic flow.
- KPP mixed layer
- Synoptic surface forcing when possible: daily NCEP state variables, ISCCP solar fluxes (monthly data or climatology), blended MSU/Xie-Arkin precipitation (monthly data or climatology). Starting 01/01/79.
- Source code: http://climate.acl.lanl.gov
- IBM SP3 @ NAVO: 500 procs. -55 model days/wallclock days
- Evaluate boundary currents, transports, overflows, water mass characteristics, energy levels.

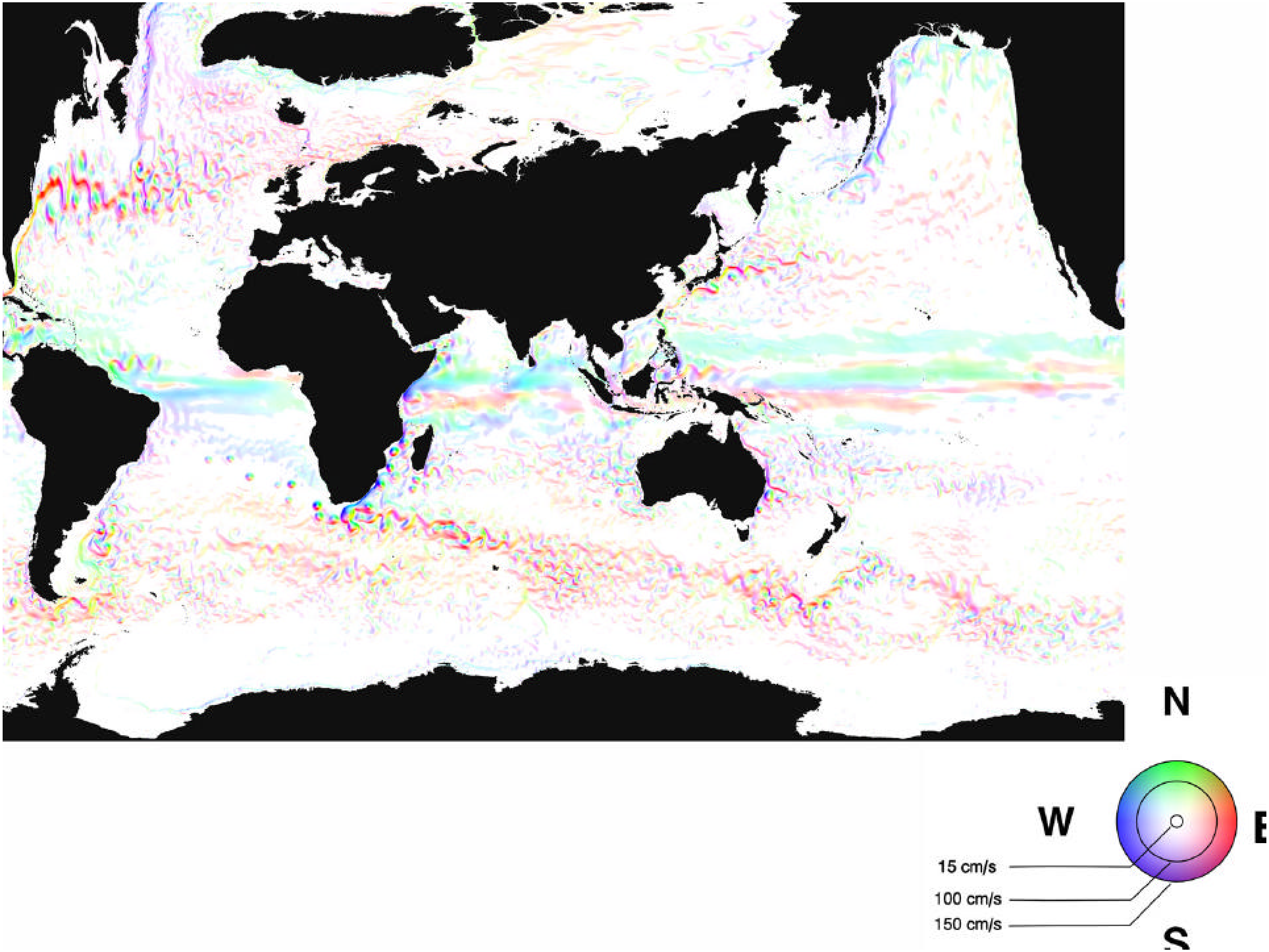
Fully Global Displaced North Pole Grid
3600 x 2400 x 40



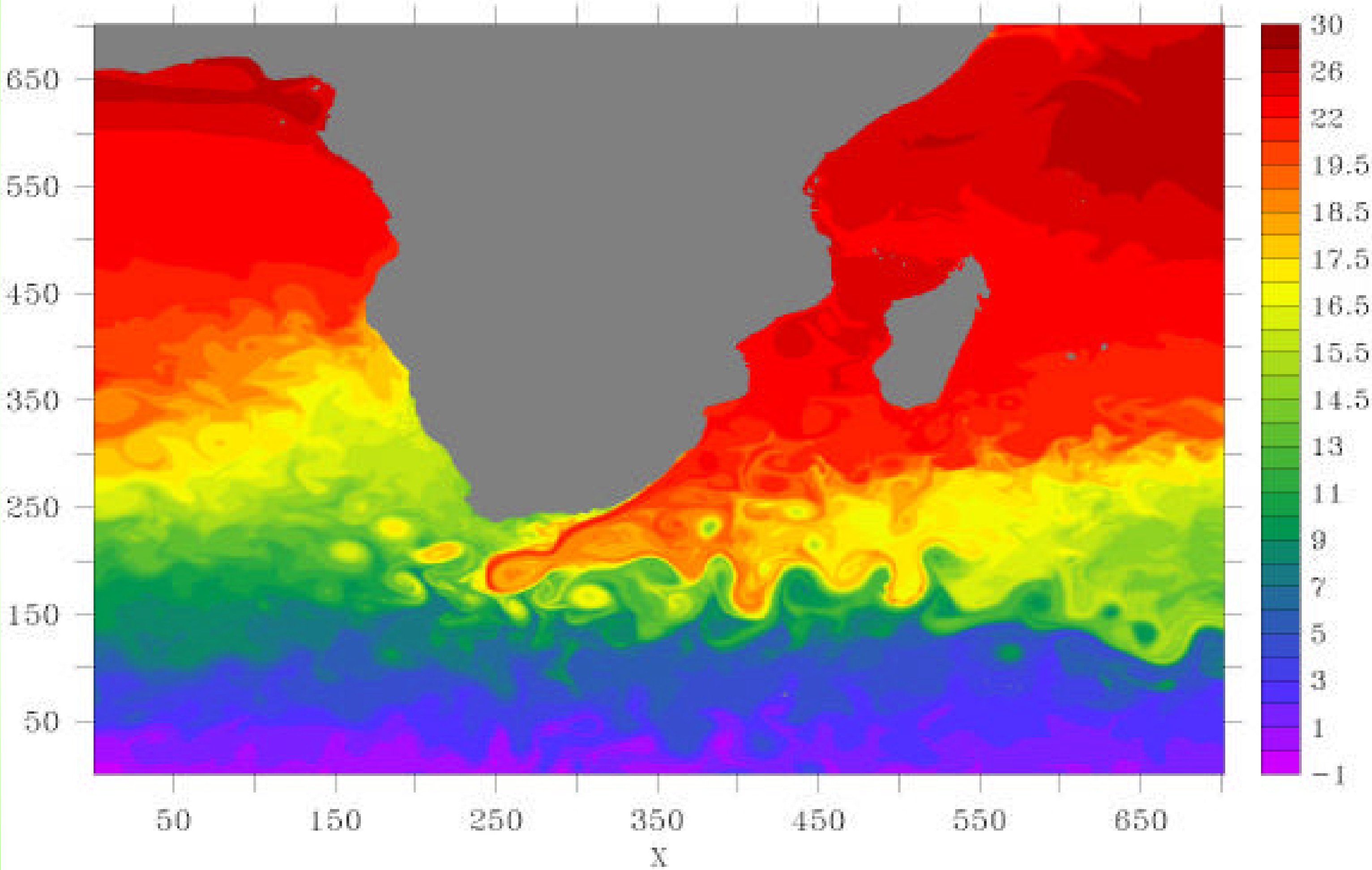
Global Spin-Up Surface Forcing

Synoptic surface forcing when possible- starting 01/01/1979:

- Daily wind stresses from 4x daily NCEP U and V.
- Daily heat fluxes from 4x daily NCEP T and q to give latent and sensible heat fluxes. Monthly ISCCP for downward solar radiation and cloud fraction (data or climatology). Longwave from cloud fraction.
- Daily freshwater fluxes from blended MSU/Xie-Arkin monthly data or climatology for precipitation & evaporation from latent heat. River input to be added.

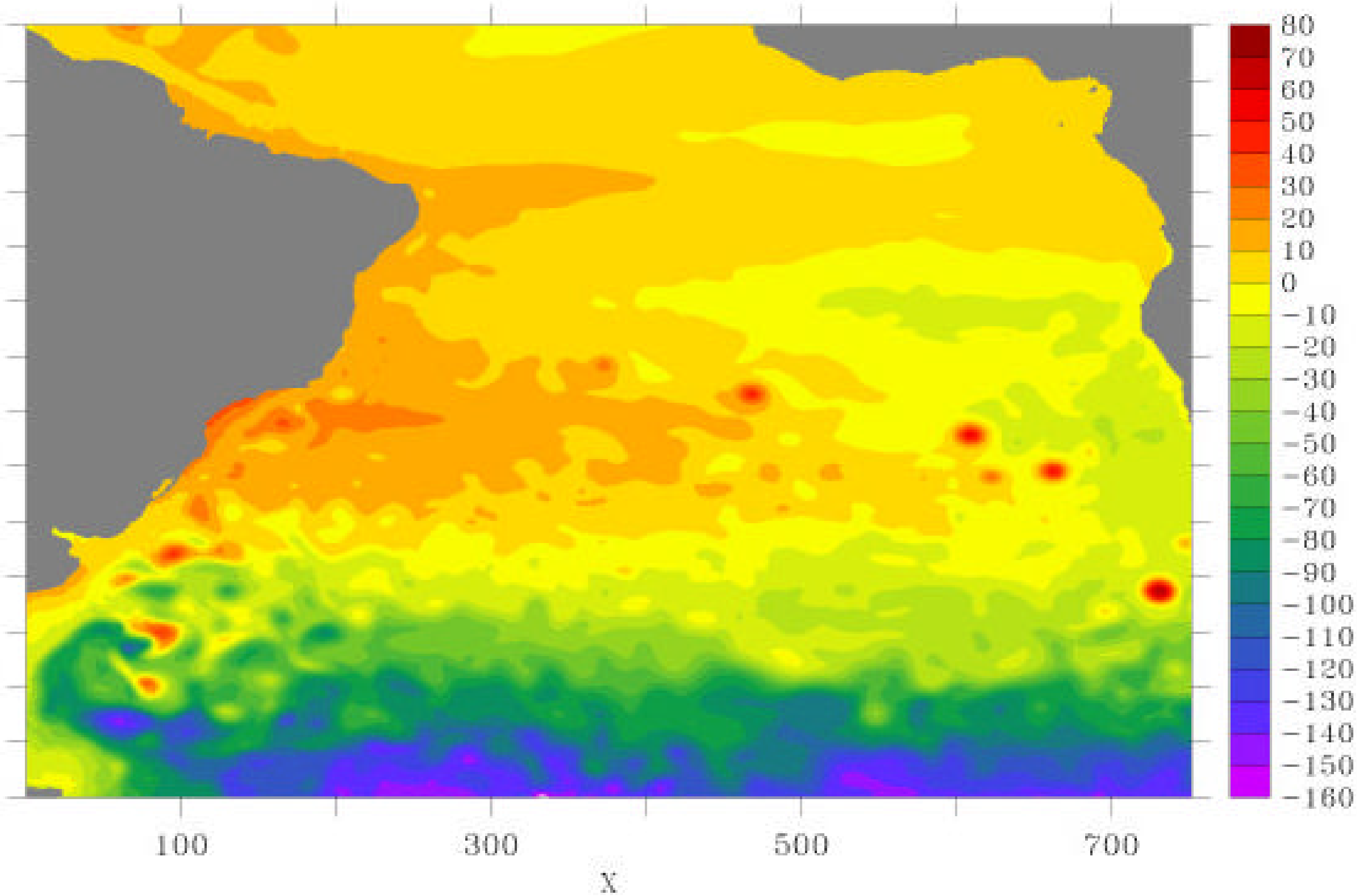

N
W
E
S
15 cm/s
100 cm/s
150 cm/s

Sea Surface Temperature (C)

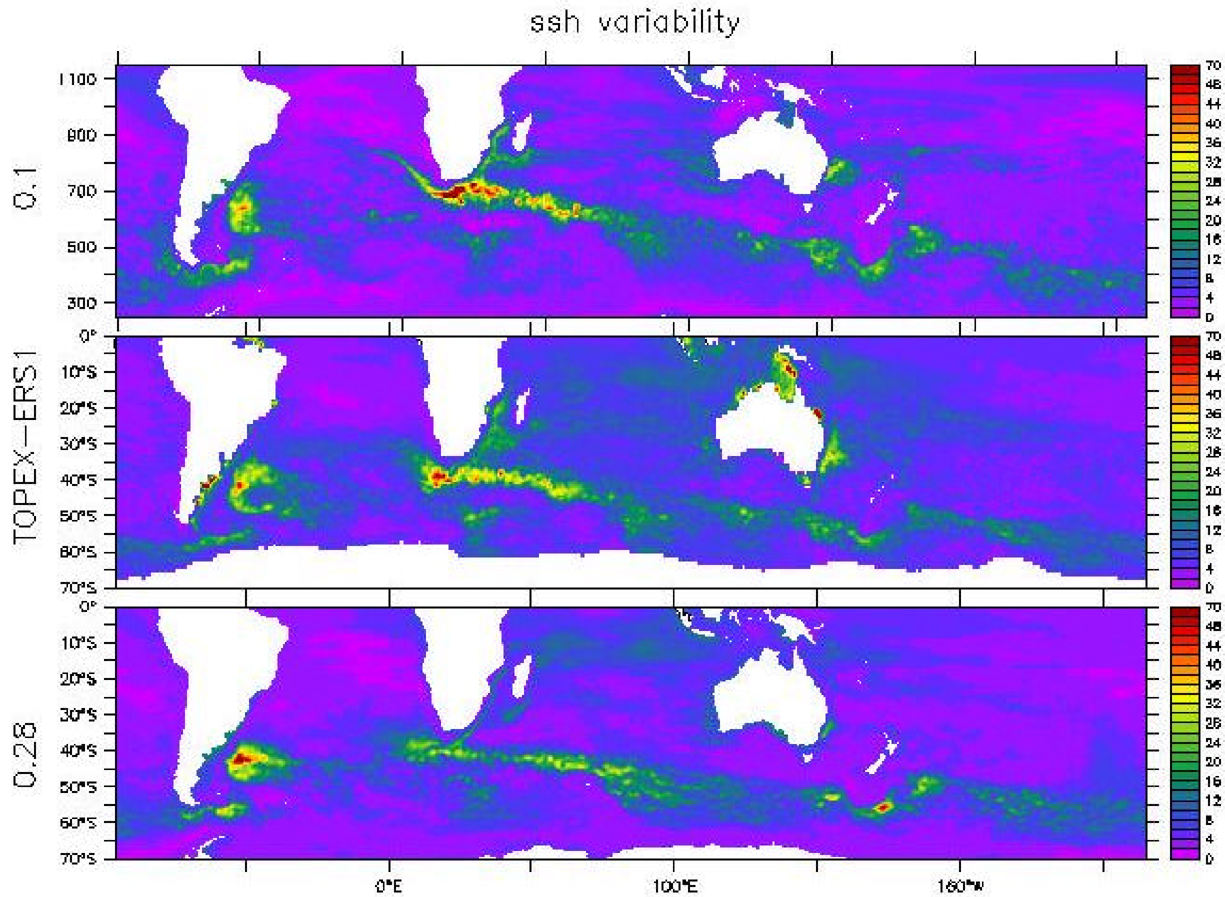


Daily snapshot: 30 August 1984

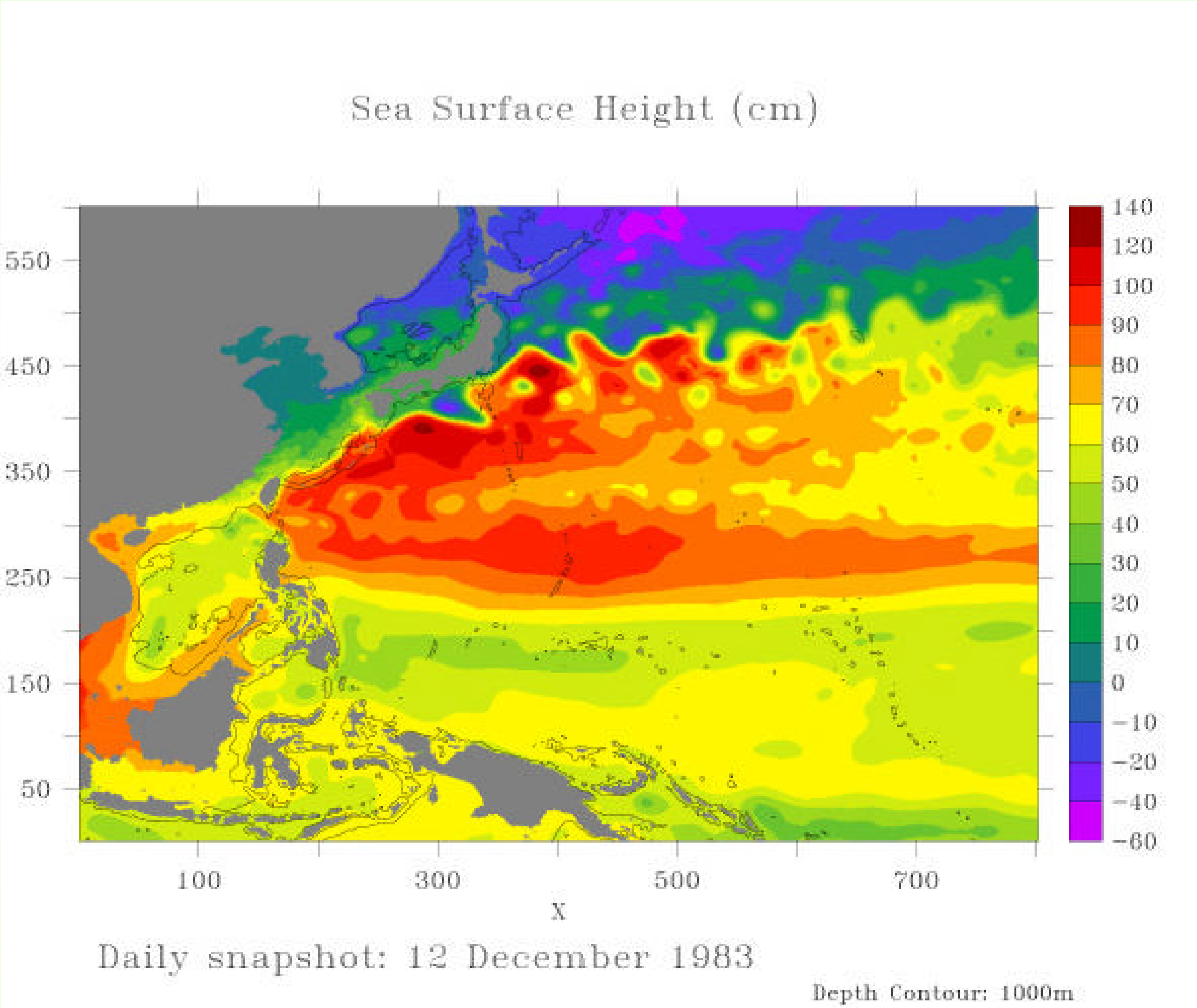
Sea Surface Height (cm)



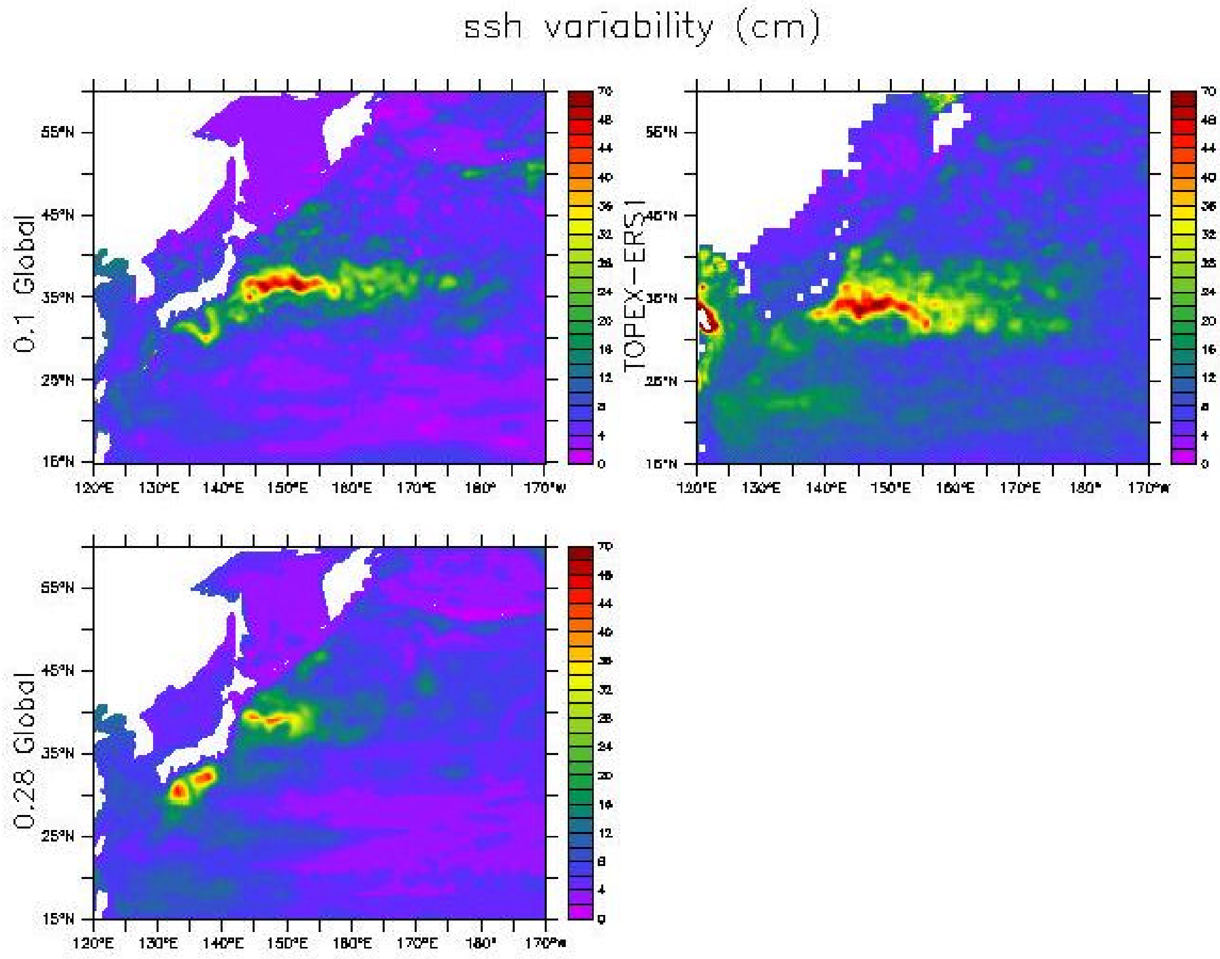
Daily snapshot: 4 June 1984



Sea surface height variability (cm) from global 0.1° POP (top), TOPEX-ERS1 (middle) and near-global 0.28° POP (bottom)

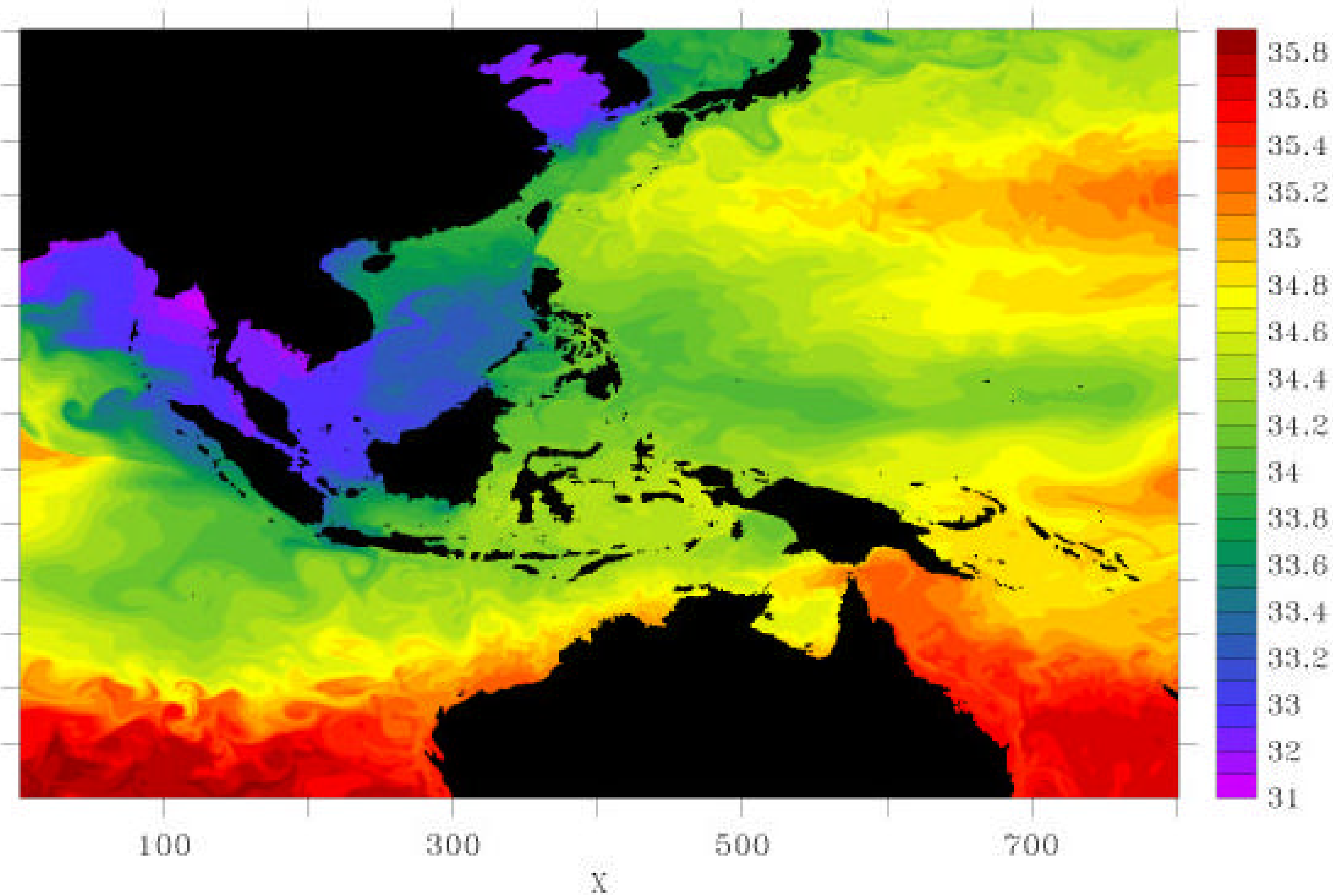


Sea Surface Height (cm)
550
450
350
250
150
50
100
300
500
700
X
140
120
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−40
−60
Daily snapshot: 12 December 1983
Depth Contour: 1000m



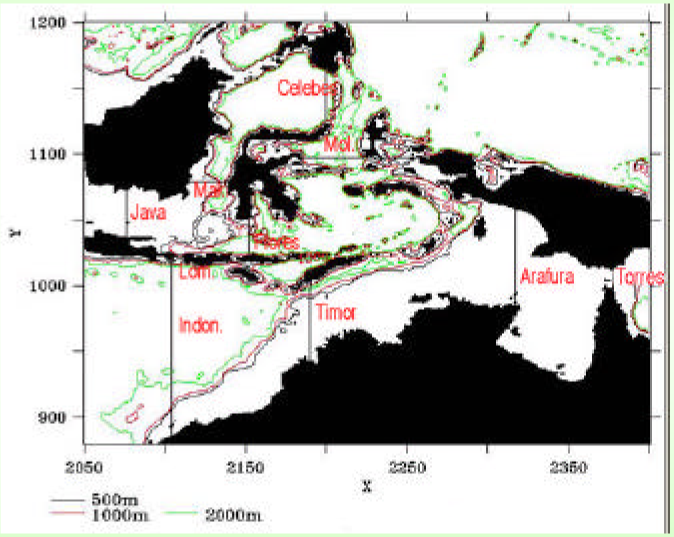
Sea surface height variability (cm) from global 0.1° POP (upper LHS), TOPEX-ERS1 (upper RHS), and near-global 0.28° POP (bottom LHS)

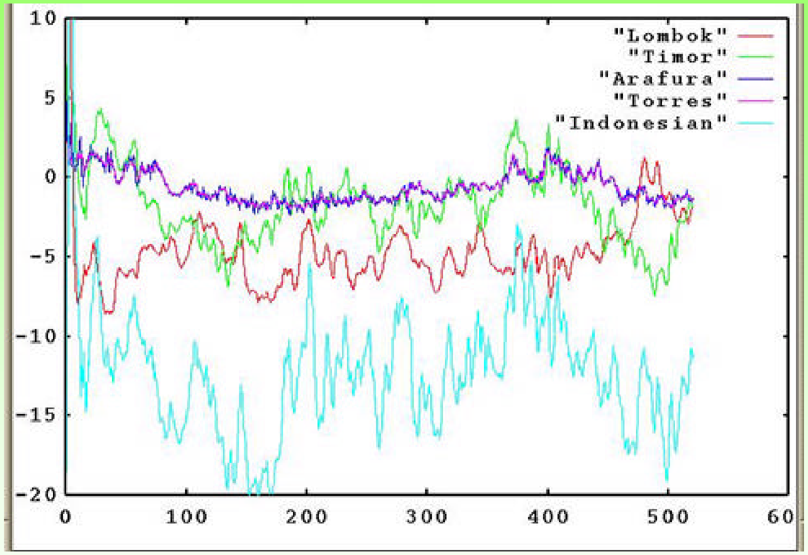
Sea Surface Salinity

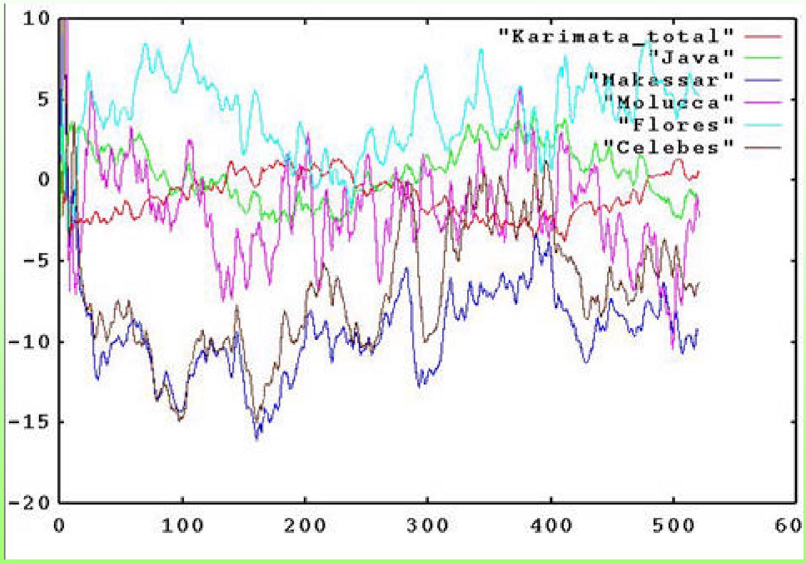


Daily snapshot: 10 August 1984

Mass Transports (Sv) through the Indonesian Seas for the first 17 months of the spin-up.

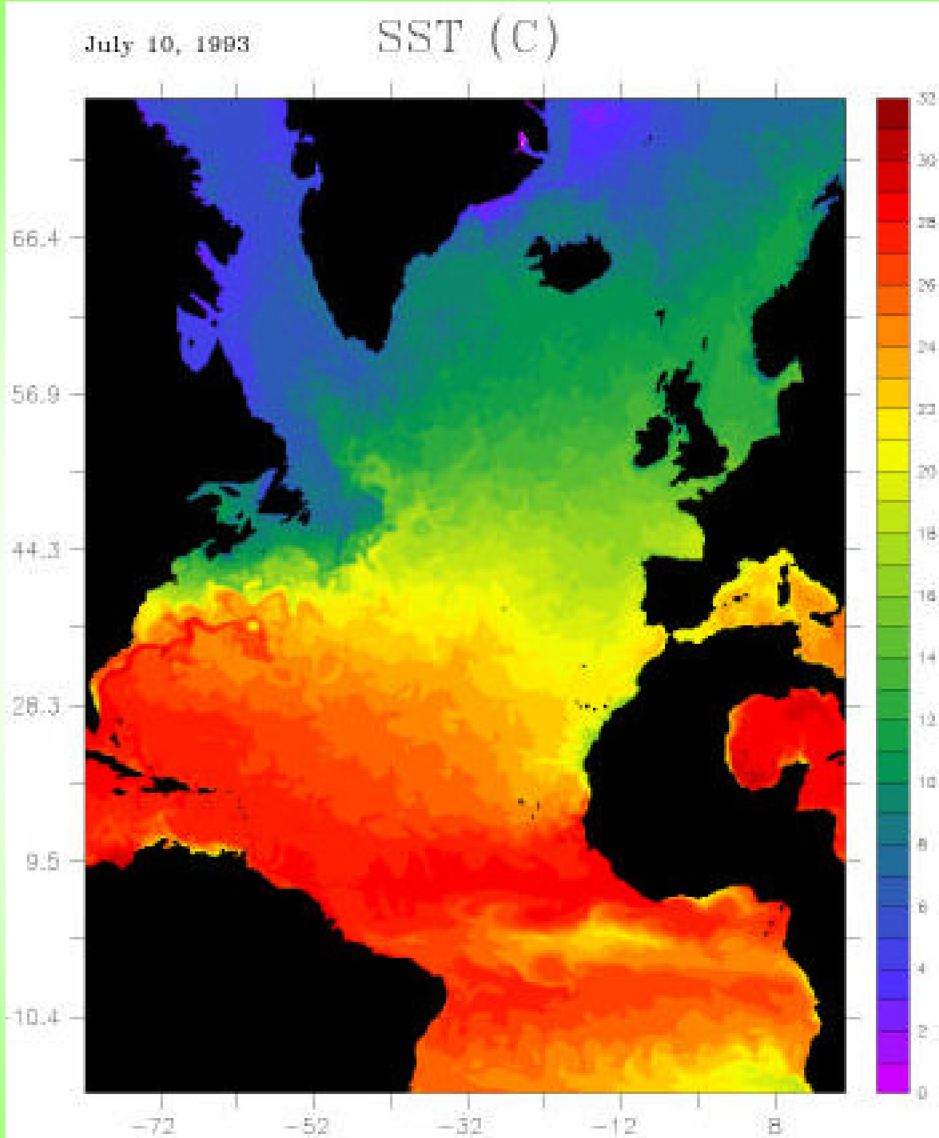






Conclusions

- Preliminary evaluations of the global spin-up show realistic development: boundary currents, marginal sea circulation, and mesoscale eddies.
- Mass transports and energy levels are realistic.



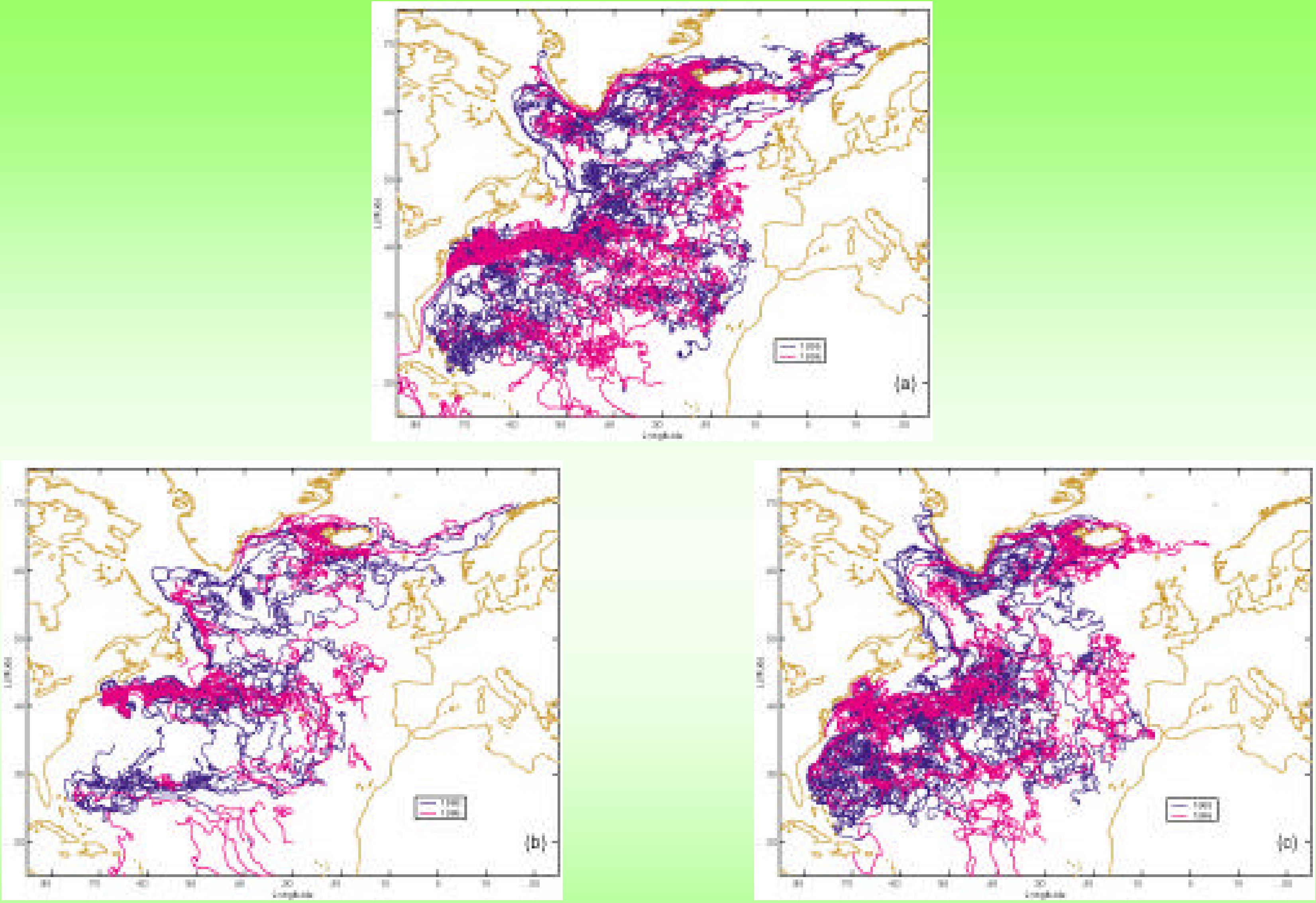
Sea Surface Temperature over the North Atlantic model domain

Approach: 0.1º, 40-level North Atlantic POP Model Description

- Multilevel PE model; Implicit free-surface
- Initialized from 15 yr run with ECMWF forcing [Smith et al., 2000].
- Forced with daily NOGAPS wind stresses (93-08/00) and Barnier seasonal surface heat fluxes. Also 96-98 with twice-daily NOGAPS wind stresses.
- KPP mixed layer
- Mercator grid: 11 km @equator 3 km @northern boundary.
- Topography: ETOPO5
- Surface salinity restored to Levitus.
- POP release June 1999
- Source code: http://climate.acl.lanl.gov
- Web site: http://www.oc.nps.navy.mil/~braccio/pop_eval
- Evaluate output statistically with drifters, tide gauge data, & altimetry.

Global Ocean Objectives I

- Determine the ability of a high-resolution (0.1°, 40 level) basin-scale ocean model (Parallel Ocean Program) to reproduce features and processes important to Navy prediction using high frequency data (surface drifters, tide gauges, and altimetry).
- Assess the role of increased vertical (20 to 40 levels) and horizontal resolution (0.28º to 0.1º). Is it justified in terms of increased computer resources?
- Use these results to guide planning for high resolution global simulation: 0.1º and 40 levels



North Atlantic (a) surface drifter tracks, (b) 0.28°, and (c) 0.1° POP numerical trajectories for 1995-1996 only.

``Eulerian and Lagrangian Statistics from Surface Drifters and two POP Models in the North Atlantic'' by McClean et al.

Anonymous ftp: knot.met.nps.navy.mil

cd /pub/mcclean/drifter_paper

Or view a virtual poster presentation at:

http://www.po.gso.uri.edu/wbc/Mcclean

Eulerian Statistics

Mean Current: $$(u_m, v_m) = \frac{1}{n}\sum_{i=1}^{n}(u_i, v_i)$$

-Daily fields, binned into 2°x 2° boxes; binary mask applied to model output.

Mean Kinetic Energy: $$MKE \equiv \frac{1}{2}\left(\langle u\rangle_E^2 + \langle v\rangle_E^2\right)$$

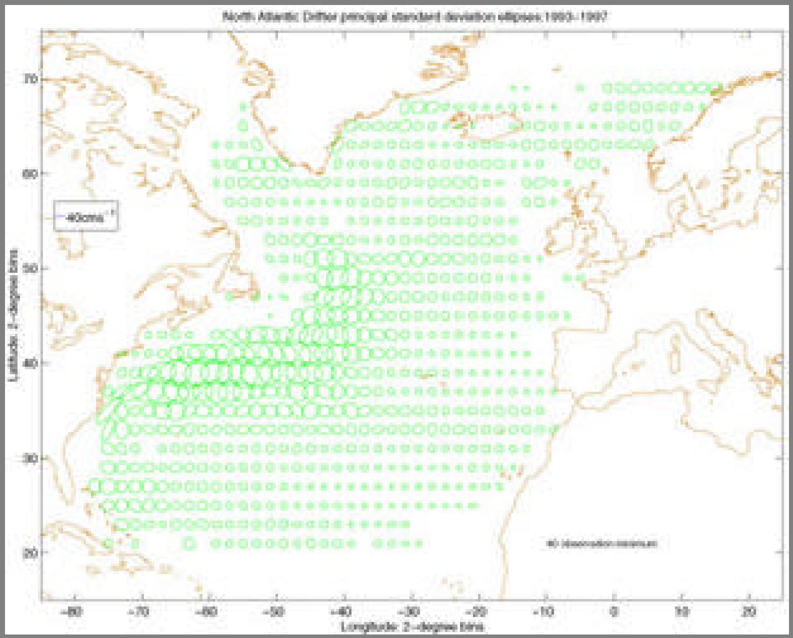
Eddy Kinetic Energy: $EKE \equiv \frac{1}{2}(l_1 + l_2)$, where l_1 and l_2 ($l_1 \geq l_2$)

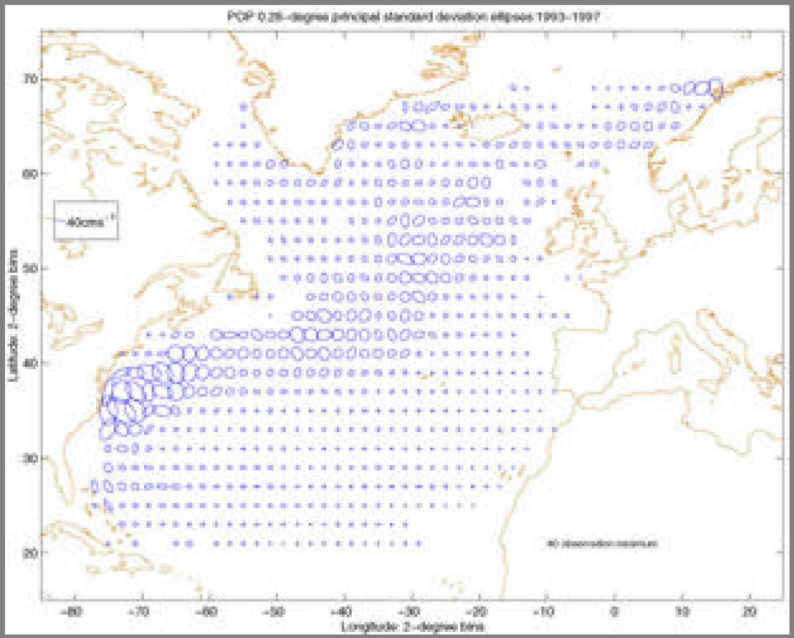
are the lengths of the principal components of variance, computed as the roots of:

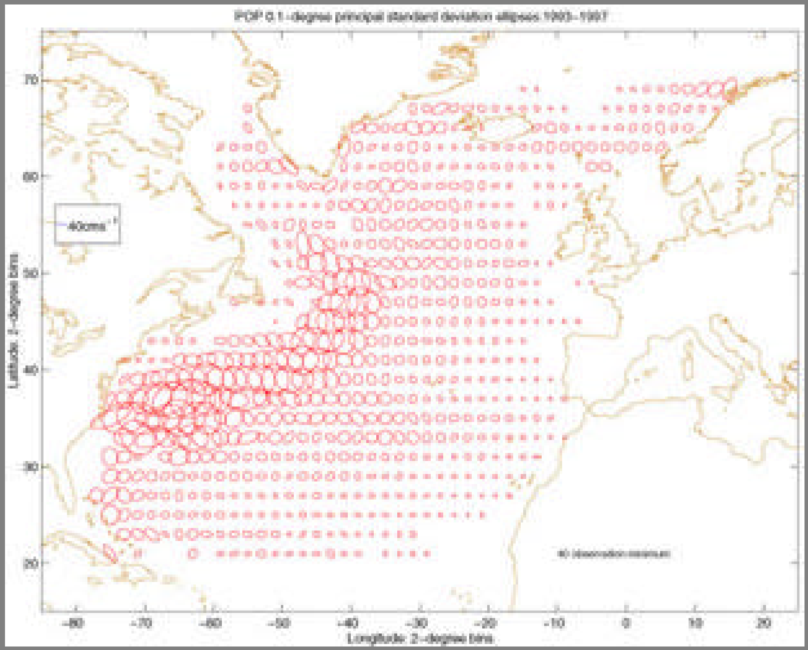
$$\left(\langle u'^2\rangle_E - l\right)\left(\langle v'^2\rangle_E - l\right) - \langle u'v'\rangle_E^2 = 0.$$

Freeland et al., 1975

Direction of Major Axis: $$\left(\frac{1}{2}\right)\tan(2q) = \frac{\langle u'v'\rangle_E}{\langle v'^2\rangle_E - \langle u'^2\rangle_E}.$$







Principal standard deviation ellipses (cm/sec) from 2°x2° binned North Atlantic surface drifter velocity data (green), 0.28°(blue), and 0.1° POP (red) velocity output for 1993-1997

Lagrangian Statistics

Define the Lagrangian mean velocity and displacement at time $t_0+\tau$ of an emsemble of particles released from **x** at time t_0 by

$$\mathbf{V}(t,t_0,\mathbf{x}) = \langle \mathbf{v}(t_0+t\mid\mathbf{x},t_0)\rangle$$
$$\mathbf{R}(t,t_0,\mathbf{x}) = \langle \mathbf{r}(t_0+t\mid\mathbf{x},t_0)\rangle$$

Lagrangian autocovariance (Davis, 1991):

$$k_{ij}(\mathbf{x},t) = -\langle v_i'(t_0\mid\mathbf{x},t_0)\,r_j'(t_0-t\mid\mathbf{x},t_0)\rangle_L = \int_{-t}^{0} P_{ij}(\mathbf{x},t')\,\mathrm{d}\tau'$$

The single particle eddy diffusivity, $K_{ij}(\mathbf{x}, t)$, or the absolute dispersion of particles leaving an area, is related to $P_{ij}(\mathbf{x}, t)$ through

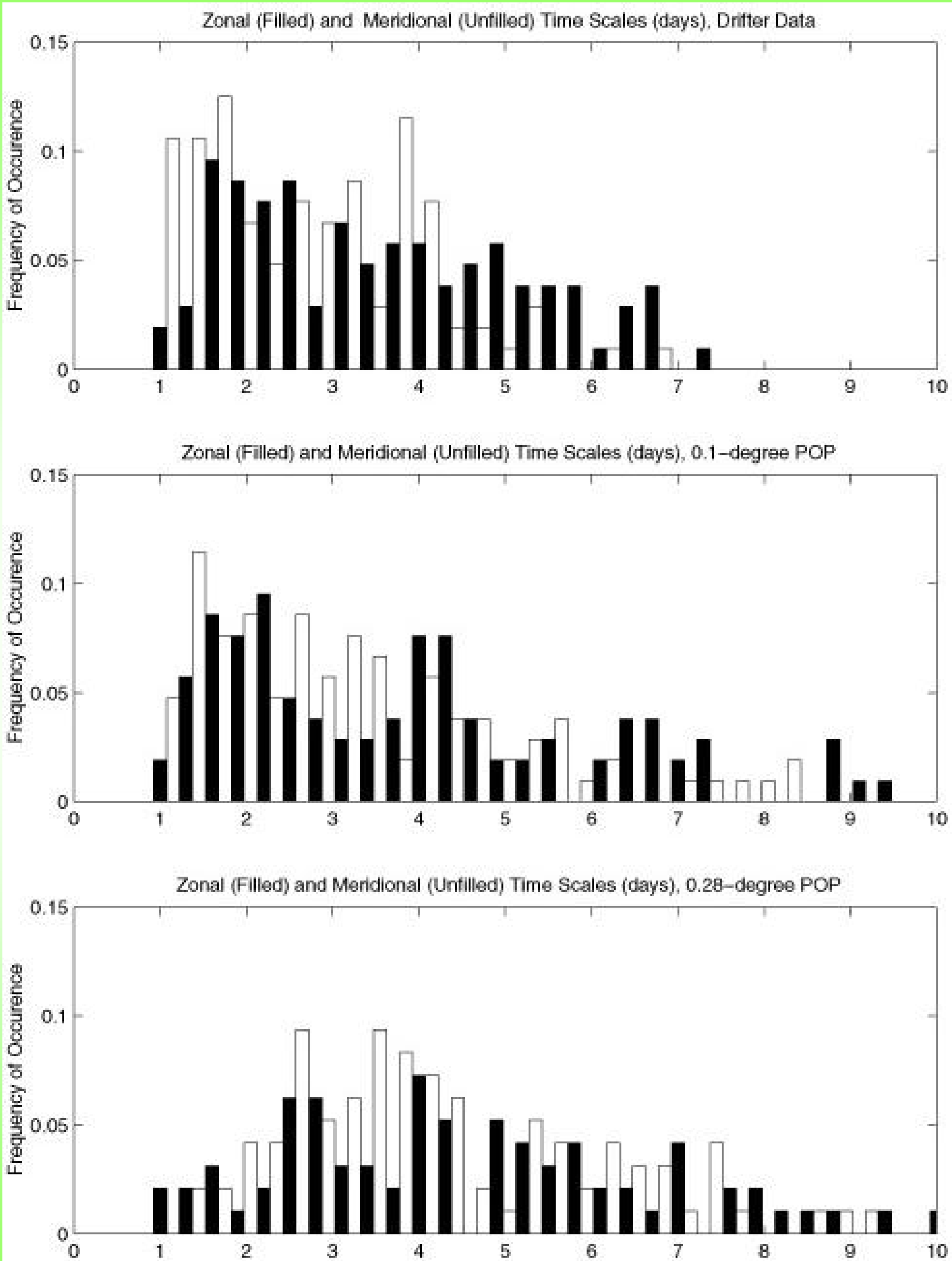
$$P_{ij}(\mathbf{x},t) = \langle v_i'(t_0\mid\mathbf{x},t_0)\,v_j'(t_0+t\mid\mathbf{x},t_0)\rangle_L$$

Lagrangian Statistics: Time and Length Scales

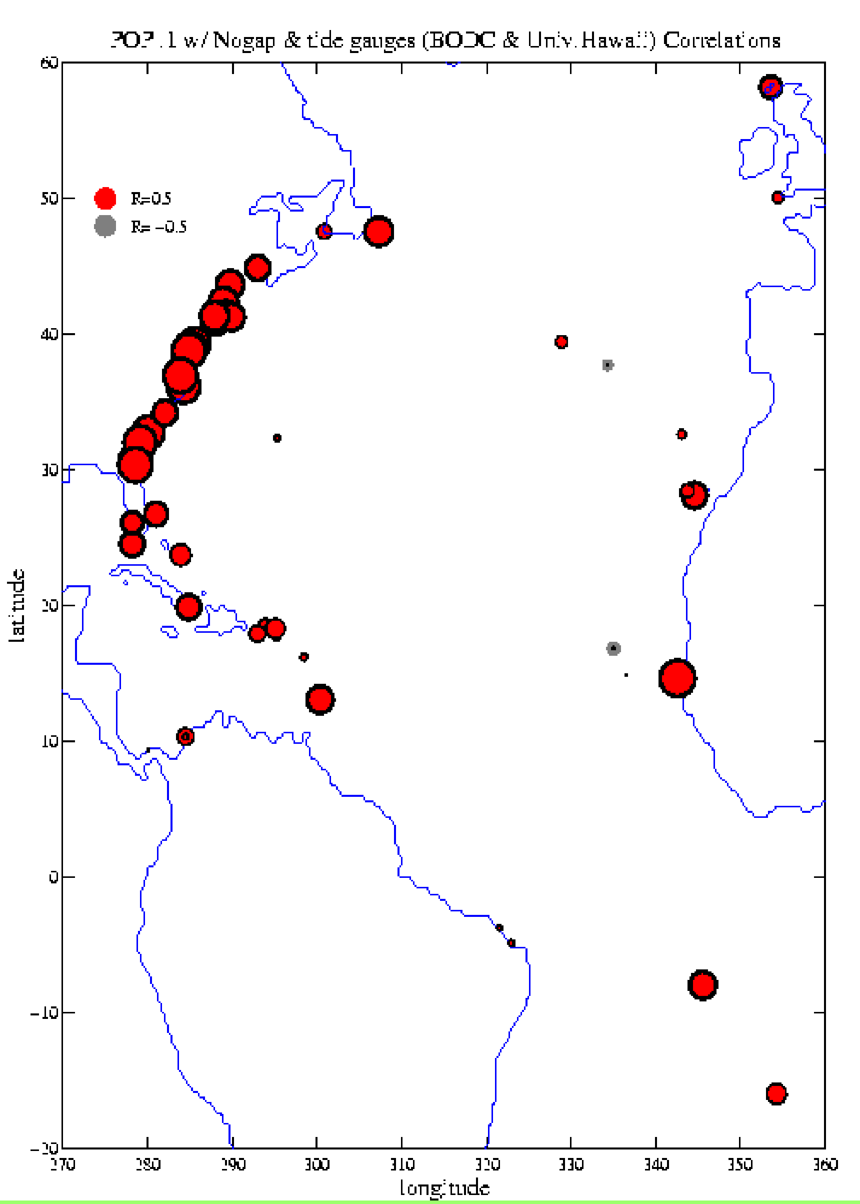
Lagrangian integral time and length scales are defined by scaling the diagonal elements of the diffusivity matrix by the velocity variance and the r.m.s. velocity, respectively. They represent the time and distance over which a particle remembers its path.

$$T_i = \left[\left\langle v_i'(t_0 \mid \mathbf{x}, t_0)^2 \right\rangle_L \right]^{-1} k_{ii}^{\infty}, \qquad i = 1, 2$$

$$L_i = \left[\left\langle v_i'(t_0 \mid \mathbf{x}, t_0)^2 \right\rangle_L \right]^{-\frac{1}{2}} k_{ii}^{\infty}, \qquad i = 1, 2$$

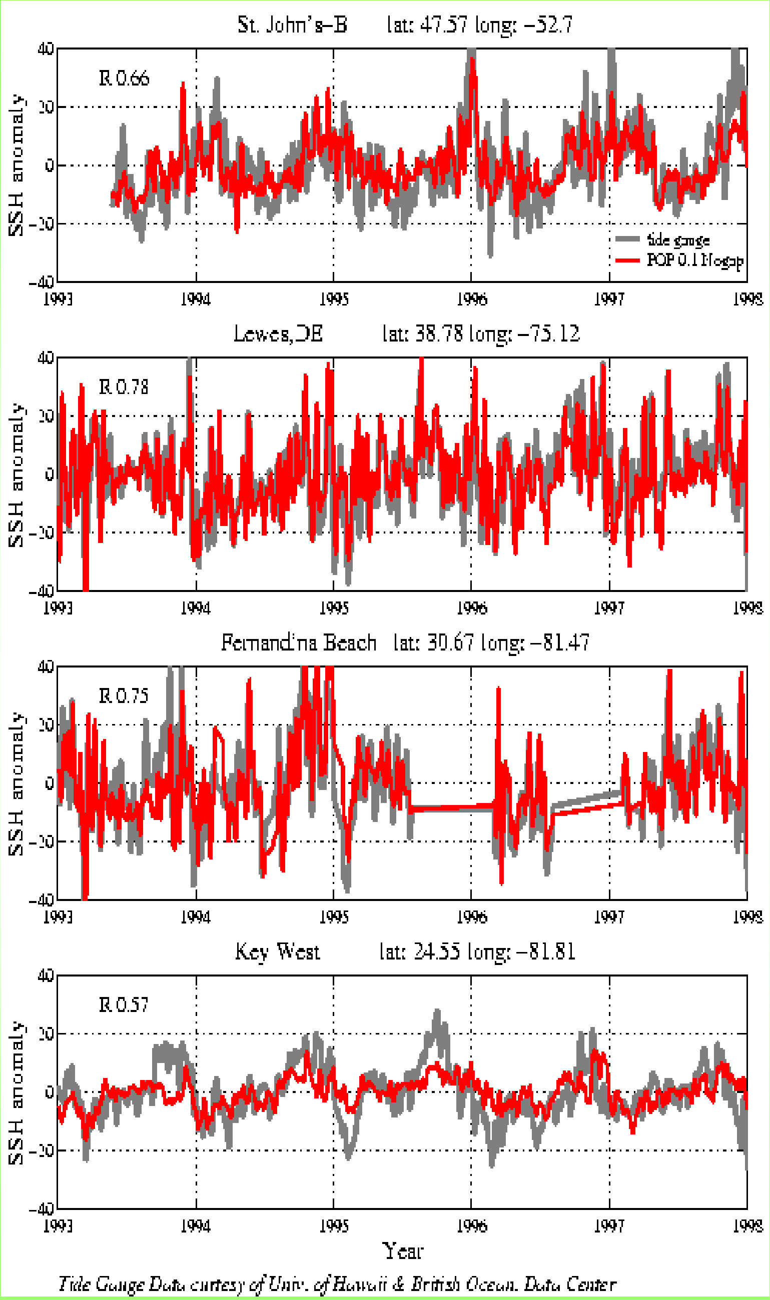

Zonal (Filled) and Meridional (Unfilled) Time Scales (days), Drifter Data
Frequency of Occurence
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8
9
10
Zonal (Filled) and Meridional (Unfilled) Time Scales (days), 0.1–degree POP
Frequency of Occurence
Zonal (Filled) and Meridional (Unfilled) Time Scales (days), 0.28–degree POP
Frequency of Occurence

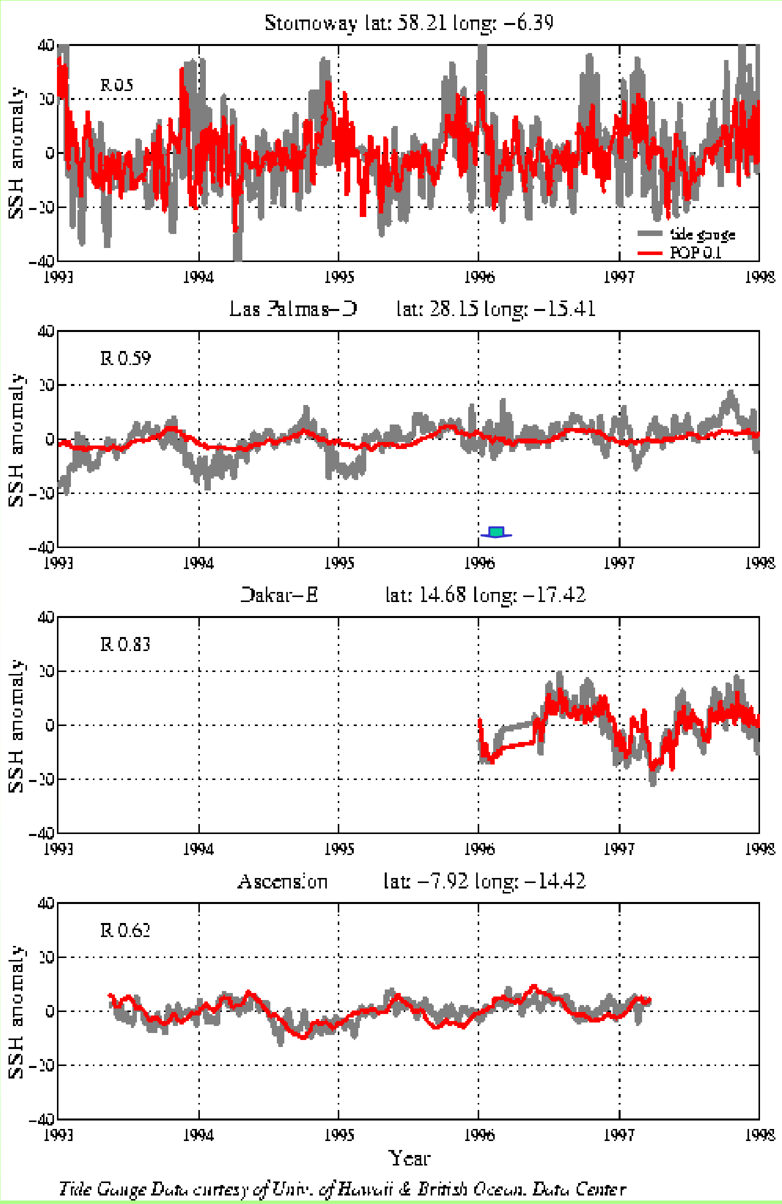
0.1° North Atlantic POP Evaluations Using Tide Gauge Data



Correlations between model and tide gauge sea surface height for 1993-1998. Circle diameter is the correlation coefficient value.

Courtesy, Robin Tokmakian





Courtesy, Robin Tokmakian

Times series of SSHA (cm) from NA 0.1° POP (red) and tide gauges for 1993-1998.

Conclusions

NA 0.1° POP statistical evaluations with

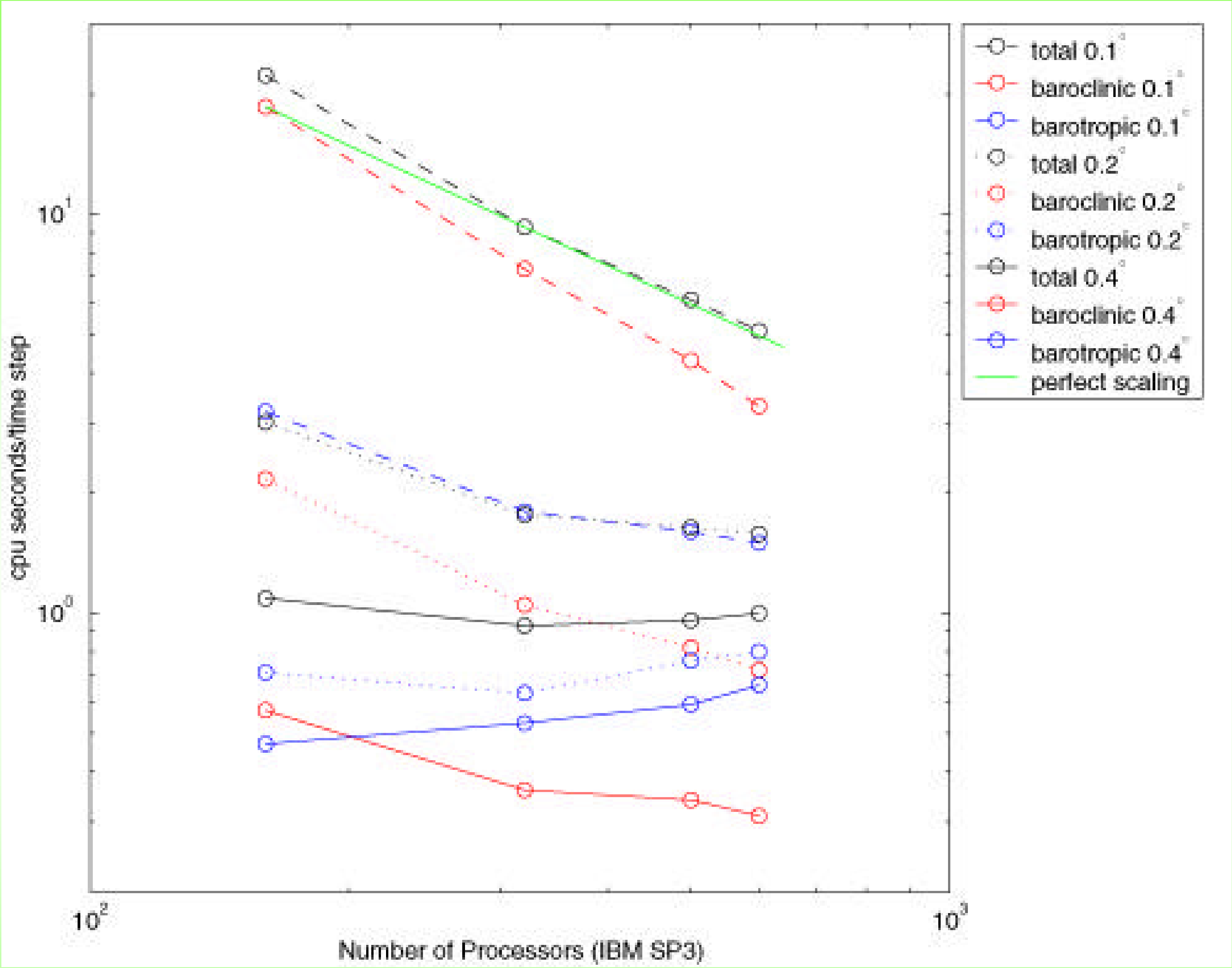
- Surface drifters: POP Lagrangian time and length scales are not statistically different from drifter scales; Eulerian velocity statistics also compare well.
- Tide gauges: Correlations of POP and observed SSHA are highest along the east coast of the US (> .50). Time-varying nature and amplitude of SSHA also well reproduced by POP.
- Altimetry: Basin-scale modes of SSHA variability from T/P closely match those from POP.

Future Work

- Continued evaluations of global spin-up.
- Continue with mixed layer depth performance runs (critical Ri no., variable Jerlov water type).
- Add rivers to E-P balance.
- Prepare NOGAPS surface forcing fields for post spin-up global run and perform simulation.
- Continue with 0.1° NA POP evaluations & analyses
  - Regional SSHA comparisons with statistical T/P model (Jacobs)
  - Vorticity and spectra from drifter tracks & numerical trajectories,.
  - Statistical analyses of Primer Experiment data (acoustic and oceanographic) and POP output (M.S student identified)

Future POP Improvements

- Partial bottom cells
- Bottom boundary layer
- Hybrid OpenMP/MPI with better cache performance
- Hybrid vertical coordinate
- Future: Vertical co-ordinate choice, physics modules.



Total (black), baroclinic (red), and barotropic (blue) timings (wall clock per time step) of global POP with horizontal resolutions of 0.1°, 0.2° and 0.4°, and 40 levels on the NAVO IBM SP 3.

POP OpenMP/MPI Hybrid: P. Jones

- Sub-block decomposition
  - Domain decomposed into blocks sized for cache (or vector)
  - Land blocks eliminated
  - Remaining blocks distributed in load-balanced manner using a rake algorithm
  - Priorities can be set to maintain some locality during rake
  - Many blocks on each node provide OpenMP parallelism
  - Block loops at high level to amortize OpenMP overhead
  - Different block distribution used for barotropic solver to optimize for communication rather than load balance

Preliminary Results: P. Jones

- Sub-blocking results in 30-40% improvement in on-node performance in baroclinic test code
  - Best improvement (40%) for largest grids
- Load-balanced distribution of blocks
  - Factor of 2 improvement (0.1 global)

Work per processor (# ocn points)			
Original Decomposition		Load-balanced Decomposition	
min	max	min	max
0	31360	14392	15841

Development and Plans for Other Components of Global Coupled Predictive System

- Atmosphere: NOGAPS (NRL, FNMOC)
- Coupler: Navy Research Laboratory (Monterey)
- Data Assimilation:
  -Optimal Interpolation (Cummings)
  -Adjoint (Bennett and Chua)
- Ice: PIPS3 (NRL, NPS)

The End